NUMERICAL SIMULATION OF EVACUATION PROCESS AGAINST TSUNAMI DISASTER IN MALAYSIA BY USING DISTINCT-ELEMENT-METHOD BASED MULTI-AGENT MODEL

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ABSTRACT

For the past few years, numerous types of disasters have drawn an array of evacuation planning approaches to support evacuation processes by obtaining the optimum practice of evacuation. This research focuses on the evacuation process optimization through numerical simulation by using DEM-based multi-agent models.

The main activities of this research are to perform numerical simulation in a way to study the influence of different evacuation scenarios on evacuation process. As for the Malaysia case study, the author studies the completion time of evacuation process in conjunction to the selection of evacuation routes and evacuation place for different scenarios. The conducts of numerical simulation are based on two different simulators developed by Gotoh *et al*. namely, (1) CBS-DE model (Gotoh *et al*., 2004) and (2) CBS-DE with self-evasive action model (Gotoh *et al*., 2012). Two different beaches in Malaysia are selected as study areas: (1) the Miami Beach, Penang; and (2) the Teluk Batik Beach, Perak.

In the first study area, only CBS-DE model is applied. The main purposes were to investigate current condition of evacuation process against tsunami and try to figure out the weaknesses in its possession. There are two hypothetical scenarios of tsunami evacuation process had been simulated in consideration, namely sim-1 and sim-2. In this case study, the assumptions are made by stating that all people need to complete the evacuation process less than 250s. The distribution of initial coordinate of the people who cannot evacuate within 250s is revealed. The significant factor of the evacuation process delay is the initial position of persons who are remote from the designated evacuation place. The alternative scenario is identified as sim-2 associated with the shortest evacuation time by introducing the new evacuation place. From the viewpoint of the evacuation completion time, a decrease of 53s is found in the sim-1 compared with the sim-2. From these results, the effect of the additional evacuation place is confirmed from decreasing of the evacuation completion time.

In the second case study, the evacuation process against tsunami disaster is investigated by using CBS-DE model and CBS-DE with self-evasive action model. In these simulations, the set-up of the evacuation route is made with a view to create contra-flow. The effects of the introducing of the self-evasive action model are validated through; (1) comparison with the observation; and (2) investigation of the simulation results regarding the position distribution of the people. The validity of the self-evasive has been shown by comparing three different results, namely model-1 (CBS-DE), model-2 (CBS-DE with self-evasive action model) and observation scene. From the simulated results the congested situation is occurred in the model-1. Meanwhile, in the model-2, the seamless alignment of pedestrian exists which is similar to the observation scene. In addition to study the effect of self-evasive action, two types of test areas are referred: the one is the area showing the contraflow, the other is the area showing the unidirectional flow. From the findings of the test area for the contraflow by the model-2, the people tend to follow the front people rather than make their own path to evacuate. This action influences the formation of alignment during the people movement in the contraflow condition. Meanwhile, in the test area for the unidirectional flow, the movement of simulated people by the model-2 is more scattered than that by the model-1. The movement of simulated people by the model-1 appears to form a

line. In the evacuation process, it is hard to consider the evacuation behavior forming a line. From this point of view, the scattered evacuation behavior by the model-2 would be natural.

The author also has put some effort in establishing its own data on Malaysian citizen average walking velocity. The analysis of the determination of average walking velocity is based on observation through video-based recording conducted during Internship program stay in Malaysia. The observation is based on the Malaysia pedestrian’s free flow located in Penang area.

All research has the goals to create new knowledge and understanding about the world and communicate the results of the research broadly. In a way to that purpose, the author created a realistic virtual space by CG movie and the visualization of the evacuation process would be a useful for giving the information to the public in an understandable manner.

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For any errors or inadequacies that may remain in this work, of course, the responsibility is entirely my own.

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CHAPTER 1

INTRODUCTION

1.1 An overview

Various parties have reported that the natural disasters incidents are increasing from year to year which give direct and indirect impact to social life. Those incidents tremendously had affected the people through infrastructure damages, crop destructions, health crises and even the fatalities. In Asia region alone, as being highlighted by Centre for Research on the Epidemiology of Disasters (CRED, 2012), the average numbers of 163 incidents of natural disaster including drought, earthquake and tsunami, landslide, storm, volcano, wild fires, extreme temperature and flood were reported from the year 2002 until 2012. Within these years about 66,644 people were averagely killed because of natural disasters incidents and more than half of the reported casualties were caused by earthquake and tsunami disasters.

The 21st century has witnessed among the worst earthquake disasters (referring to moment magnitude scale (USGS, 2012)) had ever occurred and triggered powerful tsunami. The most devastated tragedies that ever occurred were in the year 2004 and 2011. The first mentioned tragedy was known as the 2004 Indian Ocean Tsunami since it occurred at the Indian Ocean, specifically at the Sumatra region, Indonesia. The later tragedy was the 2011 Great East Japan Earthquake which occurred at the Pacific coast, specifically at Tōhoku region, near the East Coast of Honshu, Japan. Both tragedies had brought many lessons to the affected countries particularly and also to the world generally. In comparison of the number of deaths between both tragedies, the 2011 Great East Japan Earthquake had recorded lower number of deaths compared to the 2004 India Ocean Tsunami even though both tragedies had quite similar magnitude scale, (in the range of 9.0 to 9.1). Based on the damage and run-up height of tsunami at the Tōhoku area, 5% of the total amount of people who survived is very impossible without the proper design of evacuation process (EERI, 2011). Hence, lessons that can be taken from both tragedies should be utilized for planning and for taking protective arrangements to reduce destructions of both inhabitant and infrastructure is mandatory. The fatality cases would be a result from carelessness and inattention of human life. Apparently the early warning system and evacuation process should be sufficiently introduced to save thousands of people lives.

In any natural disaster tragedies post-event, where most of the structural countermeasures were destroyed, preparing smooth evacuation process remains as the most important mitigation method in order to make an effective evacuation planning. In relation to the said tragedy, the urgency of designing an effective evacuation planning is significant.

Although the conventional practice of evacuation process is evacuation drill, developing countries should use the numerical simulation as a tool to acquire an effective evacuation process because it is economical and convenient. The evacuation drill is obviously practical in real-life situations. With using numerical simulation, evacuation process can be discussed flexibly in investigating and optimizing the safety of people.

Over the past decades, there have been increasing interests in developing evacuation planning simulation (e.g., Gotoh *et al*., 2009, 2012; Park *et al*., 2004; Kiyono *et al*., 2000, 2004; Jalali, S. E., & Noroozi, M., 2009; Jiang, C.S., Yuan, F., & Chow, W. K., 2010 and Jiang, C. S. *et al*., 2009). According to available literatures, a variety of different kinds of approaches have been studied in order to develop the evacuation models (e.g., cellular automata models, lattice gas models, social force models, fluid-dynamic models, agent-based models, game theoretic models and approaches based on experiments with animals). All the above stated approaches are including microscopic models (e.g., cellular automata model, lattice gas model, social force model and agent-based model) and macroscopic models (e.g., fluid-dynamic model). Meanwhile, many studies have been performed in studying crowd behavior by using the Distinct Element Method (DEM) which employed the mechanical elements for modeling the interaction between people. The usability of the DEM to the several crowd behavior processes such as evacuation behavior against disaster has been documented (e.g., Park *et al*., 2004; Kiyono *et al*., 2000, 2004; Gotoh *et al*., 2009, 2012).

In Malaysia, tsunami phenomenon is rarely discussed and the Indian Ocean tsunami tragedy in the year 2004 was a wake-up call to make Malaysia government promptly reassess their mitigation tools. This research is objectively to investigate the current conditions of the evacuation process due to tsunami mainly at Malaysia and concerning explicitly at two different study areas. The simulation is conducted by using the Crowd Behavior Simulator for Disaster Evacuation (CBS-DE), which is based on the Distinct Element Method (DEM). Different hypothetical scenarios for the efficiency study of the evacuation are performed. Further based on the outcomes, better plan of evacuation may be proposed.

1.2 Problem statement

Following from the 2004 Indian Ocean Tsunami tragedy, the government of Malaysia had enforced the relevant disaster management agencies to look the matter in detail. The initial measures to readdress the tsunami mitigation problems towards showing the better way will be considered current condition. In conjunction to that, the tsunami emergency plan had been established which covered: (1) evaluation for awareness, preparedness of the community, local and state agencies in combating tsunamis; (2) enhancement of public awareness through education of community; and (3) the formulation of tsunami evacuation planning. Among the mentioned countermeasures, a greater attention is directed to a good planning of tsunami evacuation.

Evacuation planning is a procedure that involves the movement of people to a safer place. Currently, evacuation drills have been put in place and conducted annually by the Malaysian Meteorological Department (MMD) since 2006. The drill is one of the good indicators that show whether an evacuation will go smoothly or not and successfully or not. Moreover the drill also is an important tool for awareness to familiarize the public with evacuation procedure. However, drills alone is not enough in preparing an effective tsunami evacuation planning since it is quite time consuming, costly and furthermore, the drill is quite rigid which cannot deals with various conditions on site flexibly. Hence, in conjunction to have a better evacuation planning, the author had decided to perform numerical simulation of current conditions of evacuations process on selected areas by considering different kind of scenarios. By conducting evacuation process for different kind of scenarios, better planning of evacuation may be derived. In relation to perform numerical simulations, the DEM-based multi-agent model is imposed. The DEM is one of the Lagrangian model that could track individual evacuation behavior in detail.

1.3 Objective

In order to accommodate the main concern and challenges stated in the problem statement, the following objectives are designed so that the optimum solutions may be retrieved.

i. Investigating the effectiveness and efficiency of evacuation process due to tsunami by using DEM-based multi-agent model;
ii. Validating and comparing the effect of self-evasive action in evacuation process;
iii. Establishing data of the average walking velocity for Malaysian citizen;
iv. Making the CG movie of the evacuation process for public understanding.

1.4 Scope and limitation

The main activities of this research are to perform numerical simulation in a way to study the influence of different evacuation scenarios on evacuation process. In any studies of evacuation process, preparation of quick and safe evacuation routes is indispensable for survival. As for the Malaysian case study, the author will study the completion time of evacuation in conjunction to the selection of evacuation routes and evacuation area for different scenarios. It is easy and flexible for numerical simulation to investigate completion time of evacuation in different scenarios. The selection of evacuation routes is based on the paved and appropriate paths where the shortcut path is neglected.

The conducts of numerical simulation are performed by using two different simulators developed by Gotoh *et al.* namely, (1) CBS-DE model (Gotoh *et al.*, 2004) and (2) CBS-DE with self-evasive action model (Gotoh *et al.*, 2012). Two different beaches in Malaysia are covered as study areas: (1) the Miami Beach, Penang; and (2) the Teluk Batik Beach, Perak.

In the first study area, simulation is performed by only CBS-DE model. The main purposes in the Miami Beach case study are to evaluate current condition of evacuation process against tsunami and try to reveal the weaknesses in its possession. Hence, from the weaknesses highlighted, the suggestion of improvements will be investigate.

In the second study area, the effect of self-evasive action in evacuation process is addressed by using two models. The set-up of the evacuation route is given with a view to create contra-flow. The comparison in terms of completion time between those two models will be discussed in general. The effects of self-evasive action will be validated in comparison with the observation data.

To establish its own data on Malaysian citizen average walking velocity, the author also will make some effort. The analysis of the determination of average walking velocity is based on observation through video-based recording conducted during Internship program. The observation is based on the Malaysia pedestrian's free flow located in Penang area.

Another crucial part in this research is the distribution of the population at the study areas. The observation was conducted at the beach areas to gather the distribution of the population. Due to the time constraint the observation was conducted only during weekend. The final part of this research is producing the computer graphic (CG) movie of the evacuation process based on the simulation. The CG movie would be an understandable manner to inform the public.

This research has a few inevitable limitations especially in terms of data collection for the determination of average walking velocity and the population distribution at the beaches. Those limitations are discussed further in the future chapters.

1.5 Significance of research

This research aims to increase the level of human security in facing the succeeding tsunami attack through enhancements of evacuation process by using numerical simulation. In well-developed countries such as Japan and United State, the studies of evacuation process have become a prevalent preparation in the process of the disaster prevention. Based on the current author's literature study, there are no evacuations studies through modeling and simulation are reported in Malaysia. Due to that, this research is believed to be a starting point for further evacuation research in future, and yet, an evacuation simulator can be produced in elevating the level of well-being.

In the currents research, the simulator is based on the DEM. Comparing to other numerical approach (i.e., the Cellular automata, the Agent-based, etc.), the Lagrangian crowd behavior model through DEM model, which calculates the interactions of the individuals directly, possesses high possibility in describing the essence of the human behavior as an interaction system. The crowd can be interpreted based on the physics of a granular body, however because a person acts actively based on self-acquired information, the mathematical model of this active behavior is necessary. Although human behaviors are still complex, however, approximated behavior would be simulated by using the DEM.

1.6 Thesis outlines

This dissertation is organized into six chapters. Chapter 2 presents a literature related to evacuation process and types of numerical method. This chapter focuses on issues of emergency evacuation, existing DEM-based evacuation models, human behavior, and basic numerical scheme for the emergency preparedness.

Chapter 3 aims to elucidate the methodology applied in order to achieve the main objectives of this research. The concepts of mathematical equations involved in the CBS-DE and the CBS-DE with self-evasive action model is explained. Moreover, this chapter also discusses the methodology of data acquisition, determination of average walking velocity for Malaysia pedestrian, procedure of the software used, modeling and input data and simulation and reproduction of evacuation process result.

Chapter 4 discusses the application of the CBS-DE model to investigate the effectiveness of evacuation process at the Miami Beach, Penang. Simulation of the present circumstances (sim-1) has been performed and revealed the disadvantage area for quick evacuation. Then simulation (sim-2) under the hypothetical scenario to improve the disadvantage area for quick evacuation has been performed to investigate effective scenario from the viewpoint of evacuation efficiency.

Chapter 5 presents the validation of the Crowd Behavior Simulator for the Disaster Evacuation (CBS-DE) with a self-evasive action in the context of Malaysian walking behavior. The self-evasive action model has been introduced into the existing CBS-DE model with the purpose to simulate more realistic crowd behavior. With using the developed model, the pedestrian of the related to avoidance of collision or an alignment between adjacent pedestrians would be well reproduced in the contraflow.

Chapter 6 summarizes entirely all of the chapters and the conclusions of this research will be made. At the same time, the recommendations for future research are also discussed.

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CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter focuses on issues related to emergency evacuation, existing DEM based evacuation models, human behavior, and basic numerical scheme for the emergency preparedness. Typically, in emergency management professionals utilize a four-step process consisting of preparedness, response, recovery, and mitigation. Each of these four steps is important in its own right. For this research, the author try to minimize the disaster happened by providing rational planning for the evacuation of humans at effected area in terms of the attenuation of the level of destruction based on the number of casualty. Therefore, the author research part is referring to the preparedness before the disaster occurrence as illustrated plainly in **Fig. 2.1**.

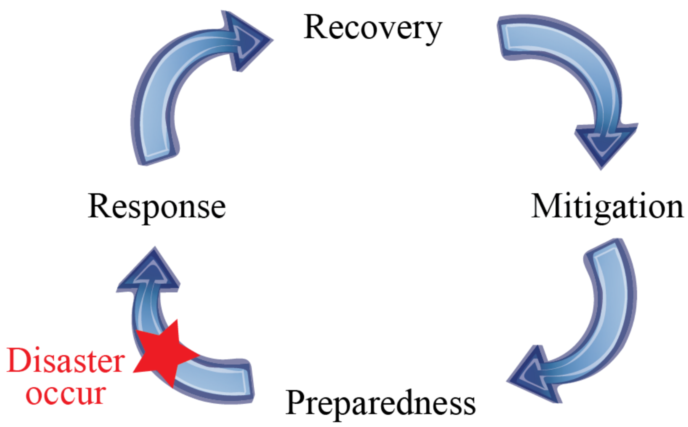

Fig. 2.1 Basic emergency management cycle

2.2 Evacuation modeling

Evacuating a large population from disasters is an extremely difficult and complicated task since that requires the coordination of several agencies. Traditionally, to ensure the safe conditions in facing the emergency case, real scene of evacuation drill is conducted. However, to demonstrate the real scene of evacuation drill involved several aspects which are *psychological*, *practical* and *financial* complication (Gwyne *et al*., 1999). The complication of psychological aspect is concerning with the threat of injury to participant and lack of reality such as panic situations. While, the practical complication is disrupt public order and wasting time involved volunteer. And the evacuation exercise should be repeated more than one time to find the optimum evacuation route or infrastructure design. In the same way, the full scale of evacuation exercise requires large amount of money in searching the volunteer to demonstrate the evacuation drill and any alteration of design is not easy. To overcome the above complications, reasonably an evacuation simulation has been used as a tool to evaluate the level of safety.

Some of the survey conducted from the previous research indicate that papers related to evacuation process can be divided into two categories: (1) evacuation in urban network (e.g.: Lindell and Prater, 2007; Lindell, 2008; Yueming and Deyun, 2008); (2) self-driven evacuation (walking) (e.g.: Kiyono *et al*., 2000, 2004; Gotoh *et al*., 2004, 2009, 2012; Langston *et al*., 2006; Smith *et al*., 2009; Sigh *et al*., 2009; Park *et al*., 2004). In general, evacuation in urban network is performed at the area hit by the disaster concerning a large radius range or long term of mitigation such as typhoon (e.g.: Lindell and Prater, 2007; Lindell, 2008;), flooding (Keisuke and Kazuo, 2008), leakage at hazardous sites (e.g.: Kiranoudis *et al*., 2002; Georgiadou *et al*., 2007), etc. The models attempt to identify the optimal lane-based in the complex of road network to minimize the evacuation time and reduce the traffic conjunction. According to the El-Sbayti (2008), the majority of evacuation model has been developed whereby the primary emphasis is on the traffic assignment.

The self-driven evacuation is usually deals with the process to evacuate people from fire or smoke hazard in building (e.g.: Weifeng *et al*., 2011; Fangqin *et al*., 2012,) or tunnel (e.g.: Capote *et al*., 2012; Ronchi *et al*., 2012). The design of building inspired by the architect progressively more complex that requires the simulation model to evaluate the level of safety for the emergency event, apart from conforming the building code (Gwyne *et al*., 1998). Currently, self-driven evacuations have also been performed to study pedestrian movement and behavior in crowd dynamic, bidirectional movement, walking at corridor and grouping movement (e.g.: Helbing *et al*., 1991, 1995, 2011; Teknomo, 2006; Langston *et al*., 2006; Smith *et al*., 2009; Singh *et al*., 2009; Steffen, 2010; Gotoh *et al*., 2011).

Assessment of computer simulation in regards to evacuation process from the building has been discussed extensively in Gwynne *et al*., (1998). From their findings, more than twenty two evacuation process models are investigating the human behavior aspect during evacuation process from building. The author stressed that the four broad areas: (1) configuration of study domain; (2) effect of environment; (3) occupants respond; and (4) evacuation procedures, should be emphasized for producing a meaningful evacuation model. However, most of the models are lack of validation because of deficiency of database suitable for validation purposes.

On the other hand, there are minimal researches had been conducted for individual evacuation model. To name a few, the evacuation against tsunami attack (e.g.: Gotoh *et al*., 2004, 2009; Sigit and Keisuke, 2011), the evacuation due to earthquake (e.g.: Kiyono *et al*., 2000, 2004), and the evacuation during emergency situations in the ship (e.g.: Park *et al*., 2004; Miyazaki *et al*., 2004). In their analyses evacuation scenarios use different kind of approaches from simple empirical models to complicated simulation model. Under the individual evacuation model, most of the models that have been formulated are utilize to investigate the behavior of pedestrians in the environment of urban areas. Moreover, simulation models offer a potential means by which planners can predict the movement patterns of large number of pedestrians as they investigate various urban spaces.

2.3 Human behavior

Human crowds during evacuation have been studied for as long as the 1930s (Kholshevnikov *et al*., 2008) and getting more attentions and becoming important research areas nowadays. Accordingly, understanding how individuals behave in evacuation situation is essential in order to model human movement during evacuations. By understanding the individuals' behavior, the dynamic of crowd behavior can be simulated. According to Helbing *et al*. (1991) human behavior is based on individual's decision. Human behavior in regards to survival aspect can be defined as the actions that people take based upon their perception of the situation, their intention to act, and the considerations involved before these actions are carried out (Margrethe *et al*., 2009).

From the literature review conducted, studies on human behavior are performed in relation to certain situations and purposes. To name a few, for example pedestrian flow (Helbing *et al*., 1991, 1995, 2011; Langston *et al*., 2006; Smith *et al*., 2009; Singh *et al*., 2009; Steffen, 2010; Gotoh *et al*., 2012), fire or smoke incident in the building (Weifeng *et al*., 2011; Fangqin *et al*., 2012), marine or ship casualties (Park *et al*., 2004) and panic situations (Helbing *et al*., 2000, Nirajan, 2012).

Helbing is well-known for the social force model, in particular its application to self-organization phenomenon in pedestrian crowds. In 1995, Helbing *et al*. suggested that the motion of pedestrians can be described as if they would be subject to social forces. These forces are not directly exerted by the pedestrians' personal environment, but they are a measure for the internal motivations of the individuals to perform certain movements. Several force terms are essential in the model of pedestrian behavior: (1) a term describing the acceleration towards the desired velocity of motion; (2) terms reflect that a pedestrian keeps a certain distance from other pedestrians and borders; and (3) a term modeling attractive effects. Computer simulations of crowds of interacting pedestrians show that the social force model is capable of describing the self-organization of several observed collective effects of pedestrian behavior very realistically.

Prior to the social force model, in 1991, Helbing studied movement of the pedestrian by producing a mathematical model for the behavior of the pedestrian. From his research the movement of pedestrians is supposed to show certain regularities which can be best described by an algorithm for the individual behavior and is easily simulated on computers. This behavior is assumed to be determined by an intended velocity, by several attractive and repulsive effects and by fluctuations.

In current research, Helbing *et al*. (2011), proposed cognitive science approach based on behavioral heuristics in determining pedestrian behavior and crowd disasters. According to them, the proposed approach is simpler than the previous approaches which are inspired by Newtonian mechanics. They claimed there are a number of limitations in physics-inspired models thus in order to overcomes those limitations cognitive science approach is applied. In their work, they had shown that two simple heuristics based on visual information can in fact described the motion of pedestrians well and that most properties observed features of crowd disasters at extreme densities.

Meanwhile Langston *et al*. (2006), Smith *et al*. (2009) and Singh *et al*. (2009) applied model originally developed by Helbing *et al*. (2000) to reproduce the numerical crowd dynamics for pedestrian behavior. Langston *et al*. (2006) introduced modeling programmer named CrowdDMX in which the DEM technique has been applied and coded in a 2D model. Then in three years next, they used CrowdDMX to study contraflow problems (Smith *et al*., 2009) and also modified the existing CrowdDMX to include realistic subgroup (Singh *et al*., 2009).

Steffen (2010) also applied model developed by Helbing *et al*. (2000) to investigate the motion of pedestrian crowds. In the paper, Steffen modified the social force model by foresight. Another paper presented on pedestrian behavior is Gotoh *et al*. (2012). The simulation of pedestrian is performed by taking a pedestrian contraflow into account. They had developed microscopic model by improving the conventional crowd simulator proposed by Gotoh *et al*. (2004, 2009). In the improved simulator, they introduced dynamic model of self-evasive action, which can treat either collision avoidance from other adjacent pedestrians or an alignment of pedestrians.

Besides pedestrian behavior, a considerable number of studies on human behavior for building evacuation have been conducted. From literature review made by Zeng *et al*. (2008), there are seven methodological approaches for building crowd evacuations have been identified. These approaches include cellular automata models, lattice gas models, social force models, fluid-dynamic models, agent-based models, game theoretic models, and approaches based on experiments with animals. In their findings, they concluded that a variety of approaches should be combined to study crowd evacuations and also incorporate psychological and physiological elements effecting individual and collective behavior into the evacuation models.

Other studies on human behavior includes Weifeng *et al*. (2011) proposed a numerical model based on cellular automata to simulate human behavior in emergency evacuation from a large smoke-filled compartment. Fangqin *et al*. (2012) present an indoor fire evacuation model by applying Geographic Information System (GIS) technology. The model can analyzed the distributions of the essential variables; i.e. building environment, occupants and combustion products and support the modeling of human-fire interactions. Park *et al*. (2004) had developed an intelligent ship evacuation model for maritime casualty. They used DEM to integrate all the forces including motions of ships to solve physical interaction of evacuees.

All the above studies are performed in the situations where humans are evacuating under non-panic situations. Human behavior under panic situations did study by Helbing *et al*. in 2000 and Nirajan in 2013. Nevertheless in this study, the simulation for evacuation is conducted for normal situations.

The dynamics of crowd behavior is important to study in order to understand the crowd motion and interaction with their environment. To model human movement in an evacuation situation with not simply but accurately, each individual would be described as a cylinder element with a set of parameters to describe gender, age and walking speed.

2.4 Discrete Element Method (DEM)

Discrete Element Method (DEM) is auspicious numerical modeling approach used by numerous scholars to perform dynamic simulations involving multiple rigid or deformable bodies, particles or various forms. The pioneer of this method proposed by Peter Cundall and Otto Strack in report to US National Science Foundation, followed by published a subsequent paper in journal *Geotechniqu* (Cundall and Strack, 1979). Through literature studies conducted, the DEM has been extensively used to simulate interdisciplinary research area. Among those areas that can be concluded are geotechnical, hydraulic, safety, chemical, food process, etc. Generally, the DEM is essentially a set of modeling techniques and equations specifically used to solve engineering problems. It models the motion and mechanical interactions for each particle in physical problems. The detailed description of velocities, positions and forces for each particle for different frame of time is provided. In DEM, a spring-dashpot system (see Fig. 2.2) is introduced to estimate the contact force between particles. It classified as a unique framework since every particle is considered as single entity in a separate particles. The method allows finite displacement and rotations of particles, with automatically recognizing a detachment and a re-contact. The interaction law between individual particles can be simulating the complex material behavior observed at a homogenized microscopic level. When the particles collide with each other, the old interaction forces had been release and the new interaction forces are produced as a result of reaction. In microscopic mechanism, the behavior of particle is controlled by the interaction between individual particles as well as interaction with surrounding particle and wall. Therefore, the detailed micro-dynamic information that is being set to each particle is obtained. The forces acting on particles are summed up and Newton's equation of motion is practiced to obtain acceleration, velocity and the displacement of each particle to update the new position of the particles at the next time step. The algorithm calculation is cycle in time-stepping, repeat application of the law of motion till the simulation is completely finished. As an illustration in **Fig. 2.3**, the overview of calculation sequence involved the DEM simulation is shown.

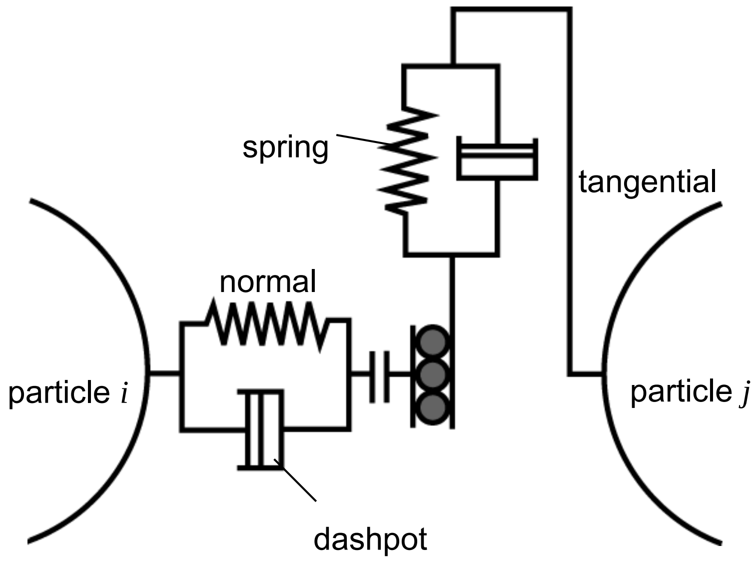

Fig. 2.2 Schematic diagram of spring-dashpot system

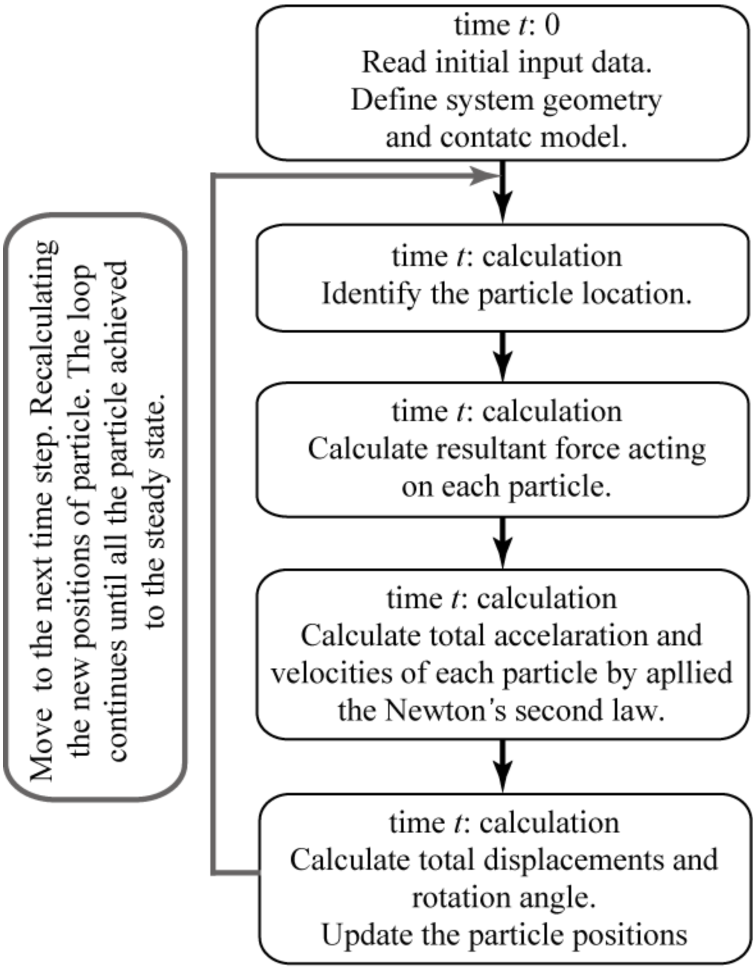

Fig. 2.3 Schematic diagram of sequence of calculation in a DEM simulation

Besides, in the research area there are several methodologies or procedures that are able to reflect as division of broad class of DEM. For example *Molecular Dynamics* (MD), *Discontinuous Deformation Analysis* (DDA), *Non-smooth Contact Dynamics* (NSCD). They can be consulted or may be classified and differentiated according to the way they deal with (1) contact detection algorithm, (2) treatment of contact (rigid, deformation), (3) deformability and material model of bodies in contact (rigid, deformable, elastic, elasto-plastic, etc.), (4) small strain or large strain formulations, (5) number (small or large) and distribution (loose or dense packing) of interaction bodies considered, (6) consideration of model boundaries, (7) possible fracturing or fragmentation and (8) time-stepping integration schemes (explicit, implicit) (Bićanić, 2007). The DEM is in the class of meshless methods that differ from the mesh methods like the *Finite Element Method* (FEM), *Boundary Element Methods* (BEM), and *Finite Difference Methods* (FDM) in several key points. However, the meshless in the *Smoothed-Particle Hydrodynamics* (SPH) and *Moving-Particle Semi-Implicit Method* (MPS) are another type of particle based models for fluid flows.

According to the Bićanić (2007), the discrete element bodies (particles) in contact are giving rise to normal and tangential contact forces. Force magnitude related to the relative normal and tangential displacement and to the relative normal and tangential velocity at the contact point. The DEM contact forces are usually calculated by introducing "virtual" springs at the contact points. The particles considered in DEM simulations are completely rigid.

2.5 Existing DEM based evacuation models

This section describes the existing models of individual evacuation. In the evacuation simulation, there are two classes of level; macroscopic and microscopic. Macroscopic level is concerned with collective behavior of the evacuees process, and that would be appropriate used to initial estimate of evacuation time. In contrast, microscopic level proves detailed interaction between each particles and flexible study relating to the crowd behavior, bottleneck and at the same time the relationship between desired velocities of people can be conducted.

Based on the current author's literature study, the earliest research on evacuation simulation integrated with DEM is conducted by Kiyono *et al*. in 1996. Kiyono *et al*. also actively presented research papers on DEM-based evacuation simulation in 1998, 2000 and 2004. Based on Kiyono *et al*.'s researches findings, the parameters such as spring constant, driving force of human and walking velocity are obtained from experiments. As quoted in Gotoh *et al*. (2012), Kiyono *et al*. in his 1996's paper had proposed DEM-based model in simulating behavior of a crowd evacuation during emergency disaster. They had used repulsive forces physically and psychologically in describing the dynamic of human movement which is based on personal space of each individual of the crowd. They observed and defined that the representative lengths scale of a personal space as a psychological radius; in which the psychological radius is the averaged relative distance between persons stopping at red light. Kiyono *et al*. also applied the Voigt model in order to estimate the repulsive force. In 1998, Kiyono *et al*. had modified model proposed in 1996 by incorporating an algorithm in which element can avoid collision with other elements. And at the same time, they had measured the physical spring constant in the normal direction (k^n =1.26 x 10^4 N/m) between pedestrian with compressing actual human body.

Besides, they also proposed the setup procedure of model constant, which is necessary for the implementation of the pedestrian simulator. Those constant are as shown in **Table 2.1**. From the table illustrated, constant 0.05 is determined through experimental trial and error. The dashpot constant is deduced from the critical damping condition of the Voigt model with a single degree of freedom. The superscripts '*n*' and '*t*' denote normal and tangential direction, respectively.

Table 2.1 Setup procedure of model constants between persons

		physical repulsive force, ***ij***	psychological repulsive force, ***ps_ij***
spring	k^n	k^n =1.26×10^4 N/m	$k^n = \dfrac{\mathrm{Ma}}{\Lambda - \frac{\mathrm{d_h}}{2}}$
	k^t	k^n ×0.05	k^n ×0.05
dashpot	c^n	$2(\mathrm{M}k^n)^{1/2}$	$2(\mathrm{M}k^n)^{1/2}$
	c^t	$2(0.05\mathrm{M}k^n)^{1/2}$	$2(0.05\mathrm{M}k^n)^{1/2}$

Next of their research, they had investigated three aspects of human behavior during evacuation in confined space representing an underground shopping center and path. The aspects are: (1) avoiding obstacles; (2) passing each other; and (3) overtaking. While in 2004, Kiyono and Miri proposed to change the algorithm calculation of human body model from circular element to elliptic element. The view range attribute of each particle is introduced. The repulsive force is activated when an element is entering the view range of other particle. Furthermore in the same research paper they had touched on the arrangement of human at high density area by removing the virtual spring so that the accident can be expressed by contacts in non-fixed distance between the elements. This made the model seen more realistic and super-high density state can be produce.

Besides, the DEM-based model also has been applied in developing the CrowdDMX in order to investigate the crowd dynamic issue (Langston *et al*., 2006; Smith *et al*., 2009; Sigh *et al*. 2009). Understanding the crowd dynamic comprehensively is very significant in designing the event involved large number of participation. Langston *et al*. (2006) presented the application of the DEM-based to simulate the human behavior in 2D situation to investigate the crowd behavior at London Underground. The investigation referred to the width of exit door for observing the maximum force generated between person to person and person to wall during crowd dynamic situation. Further development of CrowdDMX model has been proposed by Smith *et al*. (2009) to tackle the contraflow problem. In the previous model, collision avoidance is not considered and if collision between particles occurred, bounce off effect will occur between particles due to psychological space. This caused the unrealistic reactions and improvement need to be done. Subsequently, Singh *et al*. (2009) extended the CrowdDMX model by adding the extra algorithm component to simulate group behavior which represents family or friend walk together after avoidance action has been taken. The secondary attraction point is introduced to a neighbor of same subgroup. However, the maximum number of peoples move together in a group is not more than four people.

Under this particular method, Park *et al*. (2004) developed an evacuation model for human safety in maritime casualty in compliance with DEM numerical scheme. They had developed IMEX (intelligent model for extrication simulation) model, and had implemented in complex geometrical layout and motion of ship by confederation of three models: (1) evacuation model; (2) dynamic model and (3) intelligent human behavior model. The validations of IMEX model have been made based on the three core aspects which are the effect of slope variation, width exist variation and exit flow rate to comply the basis of intuition.

Gotoh *et al*. (2004) investigated the crowd evacuation process towards tsunami attack, then in 2009 proposed the extension of the usage of the simulator for a town area remodeling plan for protection against disaster of tsunami (2005) and further improved the simulator in adding the crowd pedestrian contra-flow behavior (2012). In studying the contra-flow of pedestrian, they had incorporated a self-evasive action model which can designated either collision avoidance or alignment behavior between adjacent pedestrian.

Originally Gotoh *et al*. (2004, 2005) had introduced an evacuation process simulator against tsunami namely Crowd Behavior Simulator for Disaster Evacuation (CBS-DE). The first attempt of the model had been used to investigate the evacuation process in a coastal town to establish the optimum evacuation places. The interaction force between people to people and people to wall had been considered. From previous researches, most of evacuation process results are displayed in 2D. Nevertheless in this model, 3D computer graphic has been integrated to make it more understandable in order to educate the public on the prospective situation.

From the CBS-DE that has been developed previously, Gotoh *et al*. (2012) had further enhanced by introducing the self-evasive action to study the contra-flow of pedestrian movement. In conventional simulator, only interacting forces and autonomous force of human are considered. In their latest simulator, collision avoidance from other adjacent people and an alignment of persons are being added. In addition, this model was developed because of the existing pedestrian studies are based on kinematic point of view where the dynamic behavior had been ignored. The CBS-DE with self-evasive action model is considered as a dynamic Lagrangian model. The model also contemplate the movement of the people a time step ahead in order to foresee the future movement. The validation process had been made by comparing the video image of pedestrian movement at crossing during peak hours and the obtained simulation results.

2.6 Basic numerical scheme

This part is crucial to give readers a brief and practical introduction to the numerical simulation that regularly applied for evacuation models or pedestrian models. There exist several techniques and approaches to model and simulate evacuation process and pedestrian activities. The numerical approaches that widely utilized inside those models are Cellular Automata, CA, (e.g.: Blue and Adler, 2001; Varas *et al*., 2007; Pelechano and Malkawi, 2008; Weifeng and Hai, 2007, 2009, 2011; Pereira *et al*., 2012), Agent-Based Model, ABM,(e.g.: Turner and Penn, 2002; Shendarkar *et al*., 2008; Qiu and Hu, 2010; Heliövaara *et al*., 2012; Manley and Kim, 2012) and Discrete Element Method, DEM, (Kiyono *et al*., 2000, 2004; Gotoh *et al*., 2004, 2008, 2012; Langston *et al*., 2006; Smith *et al*., 2009; Sigh *et al*., 2009; Park *et al*., 2004).The exploration into numerical methods for evacuation and pedestrian model is being actively pursued in a number of circumstances, including crowd behavior, bi-direction movement, subgroup behavior, lane formation and shortest path rule.

Based on Zheng *et al*. (2009) findings, there are different items of features identified which describe the numerical approaches. **Table 2.2** below depicts the features for CA, ABM and DEM in brief and **Table 2.3** describes each item of features.

Table 2.2 Features describing numerical approaches

Items of Features	CA	AB	DEM
Individuals/ Groups	Homogeneous	Heterogeneous	Homogeneous
Scale	Microscopic	Microscopic	Microscopic
Space and Time (SAT)	Discrete	Discrete/ Continuous	Discrete
Situations	Emergency/Normal	Emergency/Normal	Emergency/Normal
Typical Phenomena	· Effect of obstacles; · Jamming; · Competitive egress behavior.	· Rule-based behavior; · Herding behavior; · Queuing behavior.	· Pedestrian flow; · Crowd behavior; · Collision avoidance

Table 2.3 Description of items of features

Items of Features	Descriptions
Individuals/ Groups	In some models (approaches), pedestrian are ideally considered as a homogeneous individuals. However in others, pedestrian are looked on as heterogeneous individuals (groups) by the difference of characteristics (e.g., gender, age, psychology).
Scale	In some models (approaches), where collective phenomena emerge from the complex interactions between many individuals (self-organizing effects), pedestrian dynamics is modeled on a microscopic scale. In others, when a crowd of pedestrians is considered as a whole, pedestrian dynamics is modeled on a macroscopic scale.
Space and Time (SAT)	Some modeling approaches are discrete in space and time; the others are continuous.
Situations	Crowd movement is described in normal and emergency situations.
Typical Phenomena	Different behaviors can be reproduced in pedestrian flow simulations.

2.6.1 Cellular Automata Model

The Cellular Automata (CA) model has dynamical systems in which space and time are discrete. The space of Cellular Automata model is dividing into a lattice or grid, usually in square or hexagon shape and has the similar size. And each of cells can be one of several predefined states, update synchronously in discrete time step, according to a local, identical interaction rule (Sipper and Tomassini, 1998). The state of cell or its behavior is determined by the adjacent cell at the previous time step (Weifeng and Hai, 2007, 2009, 2011). Detailed descriptions of basic law of CA have been provided by Sipper and Tomassini, 1998 and Weifeng and Hai (2007, 2009, 2011).

In Cellular Automata method, the people or pedestrian is performed as entities cell. Each of cells is either occupied by one occupant or none in 2-dimension floor grid. In next time step, each of occupants chooses one direction to move based on current situation. They move in steps and randomly according to a rigid set of deterministic localized neighborhood rules to the selected cell among all adjacent cells surrounding the current position. The transition probabilities are chosen based on conservation of the momentum and energy for each passenger in collision incident occurred. In some cases, if cell that is unoccupied chosen by two passengers in concurrent on subsequent time step, it will be randomly assigned to one of them according to certain probabilities.

Preliminarily, the CA model is normally applied in dynamic traffic flow simulation as proposed by Yongtao in 1999 and Lárraga *et al*. in 2005. Referring to the achievement of vehicles simulation that utilizes this model, evacuation and pedestrian simulation has been applied in e.g.: Blue and Adler, 2001; Varas *et al*., 2007; Pelechano and Malkawi, 2008; Weifeng and Hai, 2007, 2009, 2011; Pereira *et al*., 2012. Most of these researches have focused on the human evacuation process in building contemporary to the fire situation. For example, Blue and Adler (2001) presented the use of Cellular Automata for simulating bi-direction pedestrian walkways in microscopic level. Varas *et al*. (2007) developed a simulation to investigate the effect of pedestrian movement under panic situation due to the fixed obstacles during emergency. Pelechano and Malkawi (2008) presented a review of crowd behavior simulation model by using commercial software tools for investigating the evacuation process at high rise building. Weifeng and Hai (2007) introduced the two dimensional basic Cellular Automata model to evaluate the human behavior by considering the inertial effect, group effect and unadventurous effect. Weifeng and Hai once again in 2009 and 2011 proposed evacuations simulation from a large smoke-filled compartment by reference to the effect of guiders and visibility range. Pereira *et al*. (2012) introduced the evacuation simulation in congested emergency event by incorporated the Cellular Automata for space modeling and the Schadschneider model to drive probabilities for the pedestrian motion. Regularly, simulator developed based on Cellular Automata model is non-deterministic where the pedestrians move with a certain probability to another cell.

As indicated by a few researchers (e.g.: Zheng *et al*., 2009; Yuan and Tan, 2007), CA has been successfully applied to various complex systems, such as theoretical biology, computability theory, fluid, earthquakes and traffic flow, etc. Since the last decade, CA has been applied to the simulation of pedestrian flow. As summarized by Zheng *et al*., 2009, about 17 CA-based research papers had been presented with different phenomena. And from

17 papers, three papers are combination of CA with others approaches and two papers had considered heterogonous model instead of homogeneous. And last but not least, the Cellular Automata model characterizes the idea that simple rules can generate complex patterns (Sipper and Tomassini, 1998).

2.6.2 Agent-Based Model

Over the past decade, agent-based modeling (ABM) has developed as a standardized research process which consists of a sequence of steps. The ABM is one of the numerical methods useful to simulate the activities and interactions of individual or collective agents. The ability of allowing dividing constituent systems parts into single entity components that can potentially hold their own attribute and rule set. Therefore occasionally the ABM is also known as individual-oriented model, or distributed artificial intelligence-based model. Somehow, the definition of the term 'agent' whether definition should be by an agent's application or environment is still questionable (Macal and North, 2005).

The ABM technique has been used to study crowd evacuation in various situations. In ABM, pedestrian is treated as autonomous decision-making agents and each agent makes decision based on the interactions with other agents and surrounding environment. Each agent is capable to process the information and exchange this information with other agents that interacted. Once the interaction between agents is happen, the involved agents are in turn influenced.

Generally, ABM is more computational time consuming than CA. However ABM has certain particular features that make it more beneficial. As stated in **Table 2.2**, ABM can be modeled both either discrete or continuous in space and time. According to Zheng *et al*. (2009) ABM had been combined with CA in studying variety of phenomena like lane formation herding behavior, obstacles avoidance behavior, competitive and collaborative behavior and decision behavior. This combination is significant in order to produce flexible and powerful models. It can have more than one attributes like age, gender, velocity, psychology etc. unlike CA which can only have one attribute at one time (Crooks and Heppenstall, 2012)

The ABM has been widely used due to certain benefits (as mentioned above). As quoted by Bonabeau in 2002, (1) ABM captures emergent phenomena; (2) ABM provides a natural description of a system; and (3) ABM is flexible. Emergent phenomena result from the interactions of individual entities. For example, during crowd evacuation, panic may occur due to fear feeling and uncoordinated path. And this leading to the fatalities as interactions between individual may happened whereby individual starts pushing each other and physical interactions occurs frequently. This emergent phenomenon makes them challenging to understand and envisage. ABM makes the model looks more realistic and natural. For example, it is more natural to describe how pedestrian move at crosswalk in contra-flow which creates the lane formation than to come up with the equations that governs the dynamics of the movement of the pedestrian. ABM also makes it possible to implement in the design of optimum urban planning. The flexibility of ABM can be observed along multiple dimensions. For example, it is easy to add more agents to an agent-based model.

ABM also provides a natural framework for tuning the complexity of the agents: behavior, degree of rationality, ability to learn and evolve, and rules of interactions. Another dimension of flexibility is the ability to change levels of description and aggregation: one can easily play with aggregate agents, subgroups of agents, and single agents, with different levels of description coexisting in a given model. One may want to use ABM when the appropriate level of description or complexity is not known ahead of time and finding it requires some tinkering (Bonabeau, 2002).

Agent-based models have been used to simulate the evacuation process and pedestrian movement since the early 2000. For examples, Turner and Penn (2002) presented an ABM to simulate a pedestrian movement path in the built environment based on Gibson's approach by adding the exosomatic visual. Shendarkar *et al*. (2008) presented crowded evacuation process due to the terrorist attack by involving the Virtual Reality (VR)- based Belief, Desire and Intention (BDI) software agent. Qiu and Hu (2010) conduct simulation of crowd pedestrian movement with consider the group structure to investigate the effect of grouping on crowd behavior. Heliövaara *et al*. (2012) proposed an ABM on the social force to simulate evacuation process in contraflow situation. Manley and Kim (2012) used public decision support system (DSS) in term of ownership, data scarcity and beneficiaries to be implemented ABM inside. The uniqueness of this model is they consider the individual with disabilities.

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CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter aims to elucidate the methodology in order to achieve the main objectives of this research. The conducted research is an applied research which involves a mathematical (quantitative) formulation to reproduce the phenomena that can be observed in reality. Simultaneously in this research the scientific knowledge is used to solve practical problems and improve human conditions.

As stated in the earliest chapter of this dissertation, the main objective of this research is the development of the tsunami evacuation planning in Malaysia through numerical model. Two different beach areas in Malaysia are selected, modeled and simulated by using Crowd Behavior Simulator for Disaster Evacuation (CBS-DE) developed by Gotoh *et al*. (2004). Three elements are considered in order to develop an effective evacuation system: (1) requirements for evacuation planning during tsunami event; (2) understanding current situation of research area; and (3) reproducing evacuation process in human scales.

In general, the outline of the methodology applied in this research is depicted in **Fig. 3.1**. As depicted in the flow chart, the specific problem definition in this research is crucial and need to be identified and formulated as concise as possible. The problem defined in Chapter 1 is the urgency to have a proper tsunami evacuation planning. The problem set was to investigate the process of evacuation during tsunami and to study pattern of the crowd behavior at two different locations of beaches. Currently the conventional practice in Malaysia being imposed is by conducting tsunami drills every year. However, the current practice still can be utilized with the aim of enhancement, and it can be optimized to the upper level.

From the problem definition, the general concepts of the tsunami evacuation process are formulated. Basically, the initial condition of the selected research areas is investigated. Quick evacuation from any disasters is the key issue; therefore the research areas are modeled based on the actual land use and data acquired at study area. Relevant and realistic data is utilized to scrutinize the evacuation behaviors which include local residents and transient populations like visitors and tourists and the attributes of the population (age, gender and walking velocity). Others factors like evacuation routes, evacuation places, evacuation time and the available exits also need to be considered in evacuation process. By having the initial data of current sites, the investigations of the present condition is evaluated by simulation. Based on the outcomes, the weak points of the present situations are determined and the improvements are proposed. The simulation is re-performed until an effective and better evacuation plan can be chosen from the view point of reduction of evacuation times.

As mentioned in the previous paragraph, data acquisition on the study area is the most important element to perform evacuation simulation. In this research data acquisition is divided into three components which are (1) mapping of study area; (2) population distribution; and (3) average walking velocity of Malaysian citizen. Those three components are discussed further in the next sections. In this chapter, specifically the measurement of the average walking velocity together with the outcomes of the analysis will be reported.

From the data obtained, the computer graphic modeling of the research areas is created using Autodesk® MAYA® software and subsequently the evacuation process is simulated based on simulator developed at Laboratory of Hitoshi Gotoh, named Crowd Behavior Simulator for Disaster Evacuation (CBE-DE). In the final stage, the reproduction of the evacuation process in human scale is achieved.

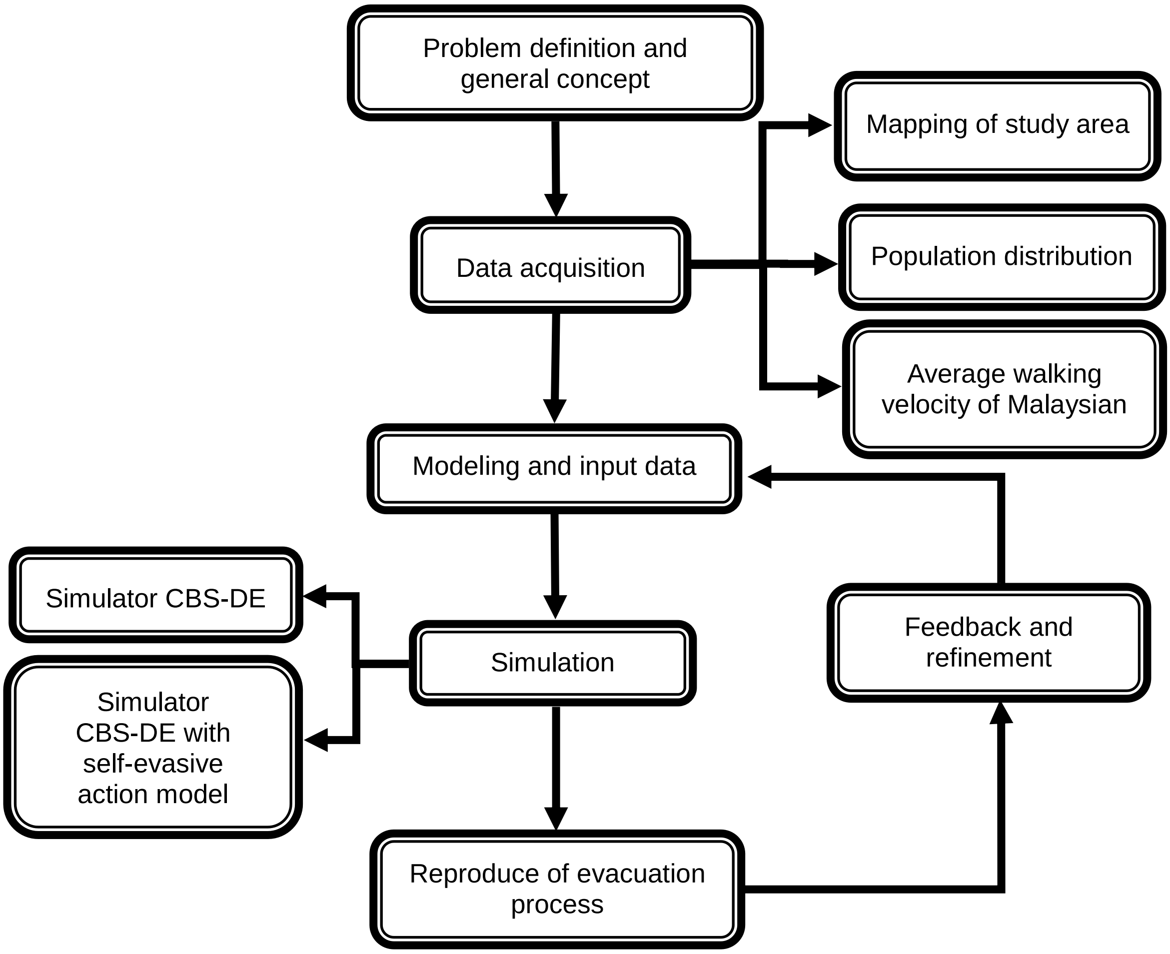


Fig. 3.1 The outline of the methodology

3.2 Mapping of study area

An accurate representation of the study area is also the important elements in this research. Later in this chapter, the modeling of the actual land use and topography of the study area is vital in order to reproduce the evacuation process in a realistic manner. In this research, topographic surveying is conducted in order to obtain the detailed descriptions of the surface and physical features that indicates their positions and elevations.

There are many definitions of surveying. One of the definitions stated that the surveying work is the science or art of making to determine the relative positions of points by measuring horizontal distances, differences in elevation and directions. The topographic survey work for this study was obtained with the cooperation from the School of Civil Engineering, Universiti Sains Malaysia (USM), Malaysia. Two survey works were conducted; first work was conducted at the Miami Beach, Penang on June 2010 and the second work was conducted at the Teluk Batik Beach on September 2011. A series of tasks is carried out to determine the coordinate of permanent natural or artificial objects on study area. It includes the elevation referring to the average sea level datum.

For this study, total station which is an optical instrument used in modern surveying had been used (see **Fig. 3.2**). It is a combination of an electronic distance measuring instruments (EDMI) and a theodolite. From the nearest bench mark (BM), the elevation should be transferred closed to the study area. Using the basic techniques of differential leveling, a level loop technique is conducted. Besides, the level loop technique is to ensure that the transferred elevation from BM to temporary bench mark (TBM) is correct.

On the TBM point, the total station equipment is established to conduct detail topographic surveying. The prisms pole was located at each of the edge object, and the readings are recorded. This step is repeated till the end of reading process for each of the permanent structure and nature.

Fig. 3.2 The arrangement location of prisms pole before the reading is recorded

3.3 Population distribution

In order to investigate crowd movement at the Miami Beach and the Teluk Batik Beach, a series of observation was carried out to gather information for numerical analysis. A human population distribution surveys for both the Miami Beach and the Teluk Batik Beach were conducted on April 2010 and September 2011, respectively. The purpose of those surveys was to ascertain the number of visitors that visit the beaches at a time and assess the capacity of evacuation facilities at the study area.

The position of the access road is identified for placing the observers in each access road for the data acquisition process. There was one observer positioned at each access road of the area. All of the observers were appointed to record the number of people entering from the access road in a unit time. The valuable information about the maximum numbers of visitors in each time is obtained. These data will be utilized during the simulation. A sketch of the position of observer setup for the Miami Beach and the Teluk Batik Beach is shown in **Fig. 3.3**.

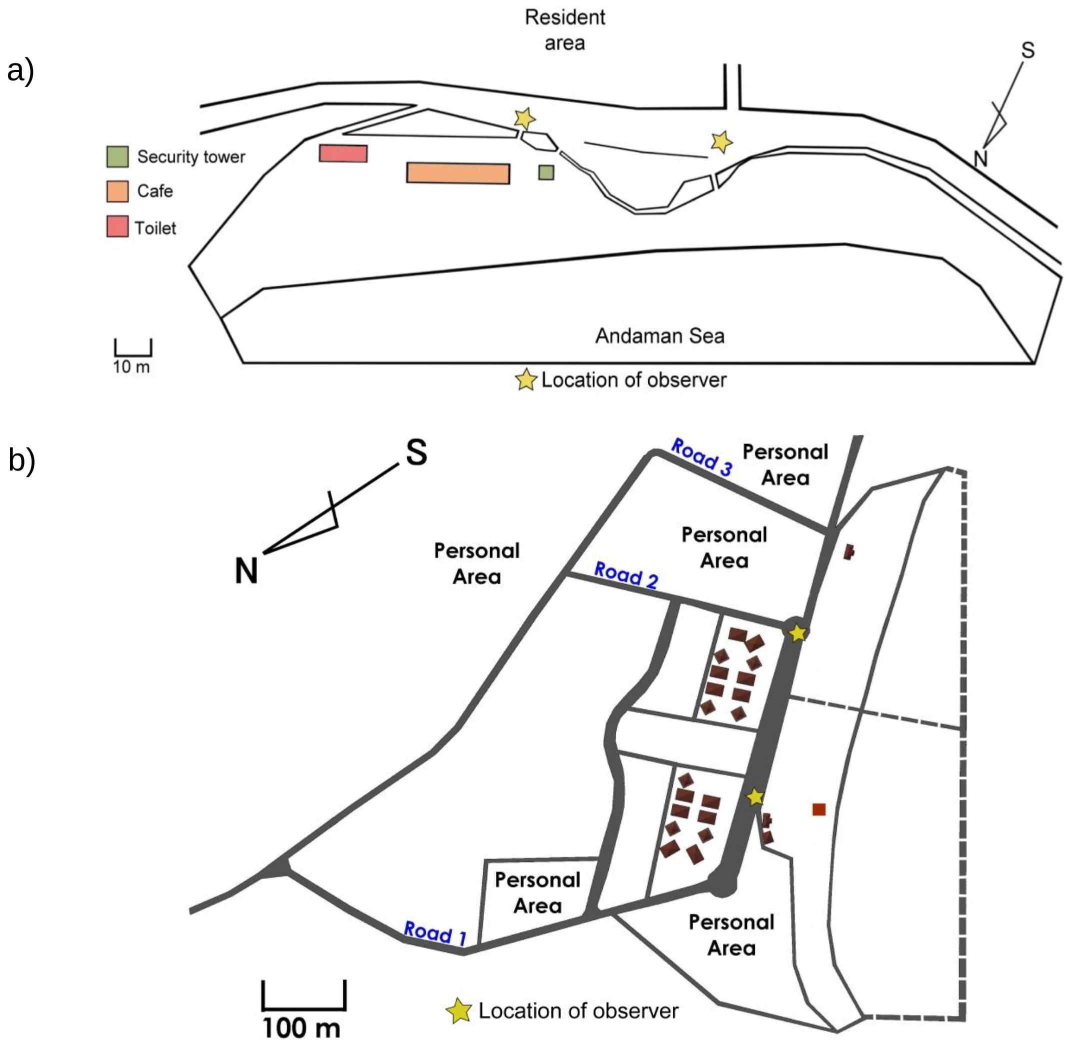


Fig. 3.3 Position of observer during population distribution survey, **(a)** the Miami Beach, Penang, **(b)** the Teluk Batik Beach, Perak

Table 3.1 Population distribution survey form

Date:		Time:		Location:	
Category	**Gender**	**Age**	**Mark**	**Total visitor**	**Ratio[%]**
1	Male	Adult			
2	Female	Adult			
3	Male	Elderly			
4	Female	Elderly			
5	Male	Over 70			
6	Female	Over 70			
7	Child	Children			
			Grand total		

A brief explanation was given to the observers before data collection process was carried out. The visitors have been categorized in 7 groups according to their age. The categories are namely children, adult men, adult women, elder men, elder women, over 70 year old men and over 70 year old women. Although the most appropriate way to identify them is by having face to face interview, but because of the limitation of the number of observers, this method cannot be applied. Therefore, other alternatives have been used, which identifies them through appearance and attire. **Table 3.1** below shows the form used by an observer to collect information.

3.4 Average walking velocity of Malaysian

Walking velocity is one of the attribute that reflect the physical behavior of each human. It can be described as a statistical distribution pursuant to several categories such as age, gender, culture, physical abilities and etc. Desired walking or equilibrium walking velocity is defined as the velocity of a pedestrian walk without hindering by other pedestrians. The distribution of walking velocity plays an important element for the implementation in many models such as evacuation models, pedestrian behavior models, traffic flow models etc., to enable realistic modeling development. This section intended to describe the determination for the measurement of Malaysian average walking velocity in detail. The walking velocity was defined in the classical way and the defined terms are to be useful for carrying out of the simulation.

For the purpose of determination of average walking velocity, the independently walking pedestrians were chosen. Basic data on walking velocity were collected from arbitrarily chosen pedestrians by on-site video-based observational recording. The pedestrian walking velocity was believed to be affected by age, gender, culture, environment conditions etc. The concept for measuring the walking velocity was based on pedestrian trajectories and from which the autonomous walking force is derived.

3.4.1 Equilibrium and average walking velocity

Velocity which is physical quantity of the rate of change of displacement for a particular element solely can be defined as a vector. In this research, the walking velocity is referring to the rate of change of pedestrian's trajectory with the certain time interval. In the present study, the assumption is made that each pedestrian is able to walk with the specific equilibrium velocity. And the equilibrium walking velocity has been used in this research. Suppose that when a pedestrian experience a loss of velocity he/she will uniformly accelerated in a constant pace until an equilibrium velocity is reached.

The equilibrium walking velocity has the upper bound of velocity for particular types of human and it is strongly influenced by the number of density of pedestrian. In calculating the equilibrium walking velocity, the average walking velocity by taking into account age and gender of the pedestrian, is focal. In summary, if the pedestrian perception domain is considered, the equilibrium walking velocity can be described as a function of the average walking velocity and density of pedestrian in the perception domain.

$$u_{limit} = u_{hi} - \gamma \cdot c \quad (3.1)$$

where $u_{limit} =$ the specific equilibrium walking velocity, $u_{hi} =$ average walking velocity of pedestrian, $\gamma =$ parameter for the attenuation effect due to congested condition in the designated area and $c =$ the number of density of pedestrian inside the designated area (perception domain).

In respect to the density of pedestrian (c), the direct definition is used which is the ratio of the number of pedestrian (N) in the perception domain of the area (A).

$$c = \frac{N}{A} \quad (3.2)$$

The value of the average walking velocity is obtained in the measurement of velocity from the on-site video recording of the independently walking pedestrian. The measurement of average walking velocity is determined by taking into consideration of age and gender of the pedestrian. The detailed determination of pedestrian average walking velocity is described further in the next section.

3.4.2 Site selection and crossing observation setup

The observation of pedestrian crosswalk was made at one of the frequently used crosswalk in Penang, Malaysia. The pedestrian movement characteristics are recorded using the videotape. The suitable location for placing the video recorder is from the top angle of video view and the movement of pedestrian is recorded from one end point to another end point of the crossing road. **Fig. 3.4** shows the observation area of pedestrian movement. The total dimensions of the crosswalk are in 12.6 m length and 4.6 m width. Pedestrian traffic across the crosswalk was observed totally in 3 hours for three different days between peak hours from 1.00 p.m. to 2.00 p.m.

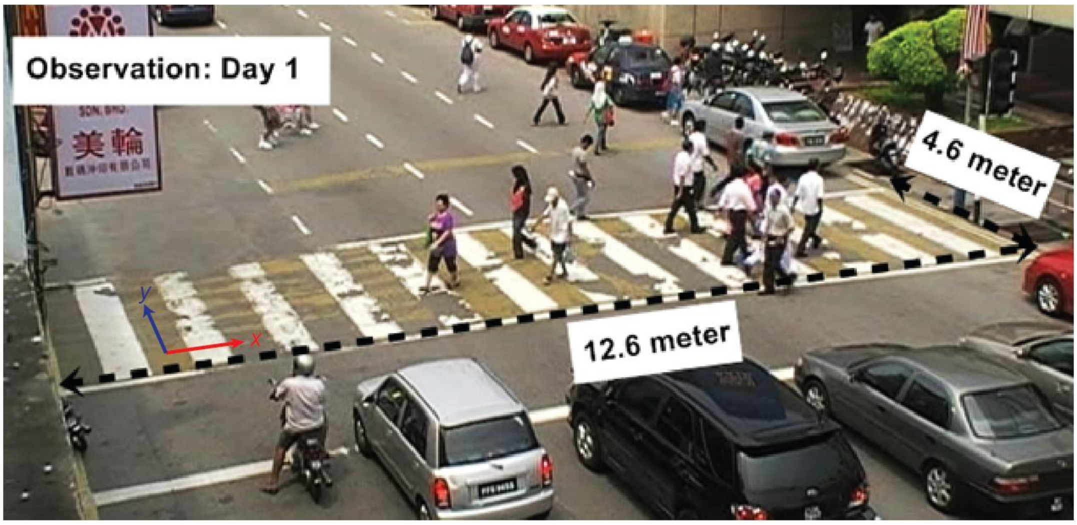
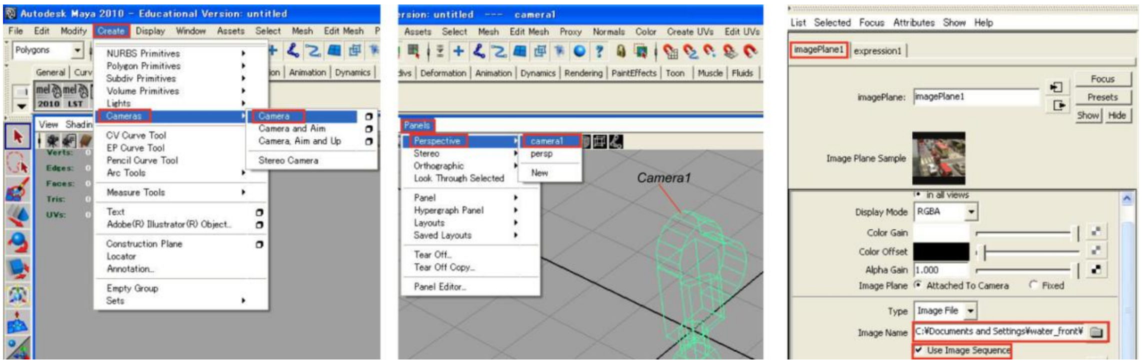


Fig. 3.4 Pedestrian crossings the crosswalk

3.4.3 The measurement of average walking velocity

From the conducted observation of the independently walking pedestrian at crosswalk, the video recorded were analyzed by using the Human Behavior Simulator plug-in into the software of the Autodesk® MAYA®. The video has been converted from the video format (.avi) to the sequence of image (.jpeg) by using the software of the Adobe® After Effects CS4 for every 0.5 second. Afterward, the sequence images were imported into the software of the Autodesk® MAYA® and the determination of pedestrian positions are executed through the following procedures:

1. Import sequence of images into the software Autodesk® MAYA®.
    i. Primarily the new camera need to be created by selecting <u>create</u> > <u>cameras</u> > <u>camera</u> (see **Fig. 3.5 (a)**). Then <u>camera1</u> will be created instantly.
    ii. To view through the new created camera (<u>camera1</u>), <u>panels</u> > <u>perspective</u> > <u>camera1</u> is selected. Now, the perspective view should be from the viewpoint of the <u>camera1</u> (see **Fig. 3.5 (b)**).
    Then, from the attribute of the <u>camera1</u>, the <u>cameraShape1</u> tab is selected. From the selected menu, in the <u>environment</u> section, the <u>Create</u> button is click and directly <u>imagePlane1</u> is initiated.
    iii. In <u>imagePlane1</u>, <u>Image Plane Attributes</u> is selected and the <u>Image Name</u> button is click to select the sequence image of pedestrian movement. Click check in <u>Use Image Sequence</u> (see **Fig. 3.5(c)**).



(a) (b) (c)

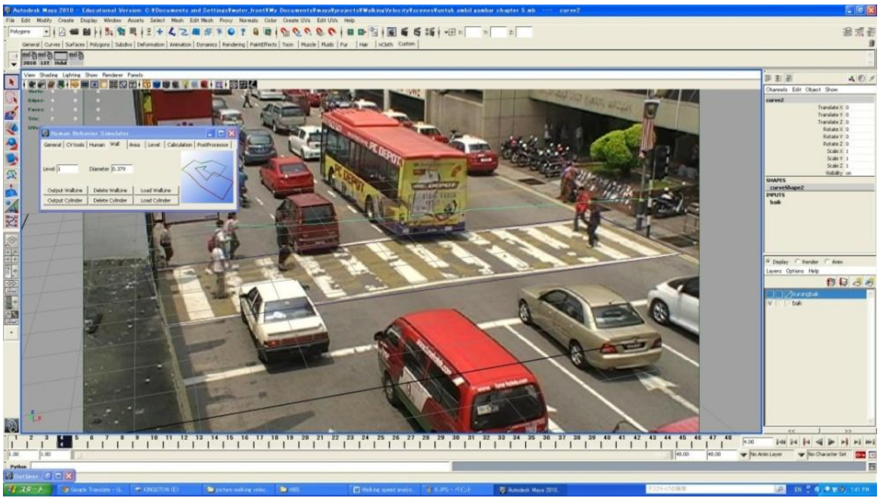
Fig. 3.5 (a) Create the new camera, **(b)** change the perspective view to look through camera1, **(c)** import the sequence images

Fig. 3.6 The rectangular polygon drawn in accordance to the ratio of actual dimension to fit with the sequence image in scale adjusted process

2. Scale adjustment
   i. From the top view in the Autodesk® MAYA®, the rectangular polygon is drawn according to the dimension of crosswalk with the ratio 1:1 scale between reality and the Autodesk® MAYA®.
   ii. By returning to the camere1 view, the position of camera1 view is adjusted to fit with the rectangular polygon drawn in step 2(i) above. The procedure is shown in **Fig. 3.6.**
   iii. After satisfying with the position of the rectangular polygon inside the sequence images, the position of camera1 is locked by clicking the channel box and selects the coordinate of camera1, and lock for maintaining the position.

3. Ascertain position of pedestrian
    i. The position of pedestrian is determined by using the <u>EP Curve tool</u>. The head of pedestrian is used as the reference to appoint the coordinate. The <u>time slide</u> is moved and the "mark" is executed.
    ii. After completed tracking the pedestrian route, the track lines is selected (**Fig. 3.7(a)**). Then, from the <u>Human Behavior simulator</u>, the <u>Wall</u> menu is selected and the button of <u>output cylinder</u> is click as shown in **Fig. 3.7 (b)**. The detailed coordinate within the 0.5 second time interval is recorded.

(a)



(b)

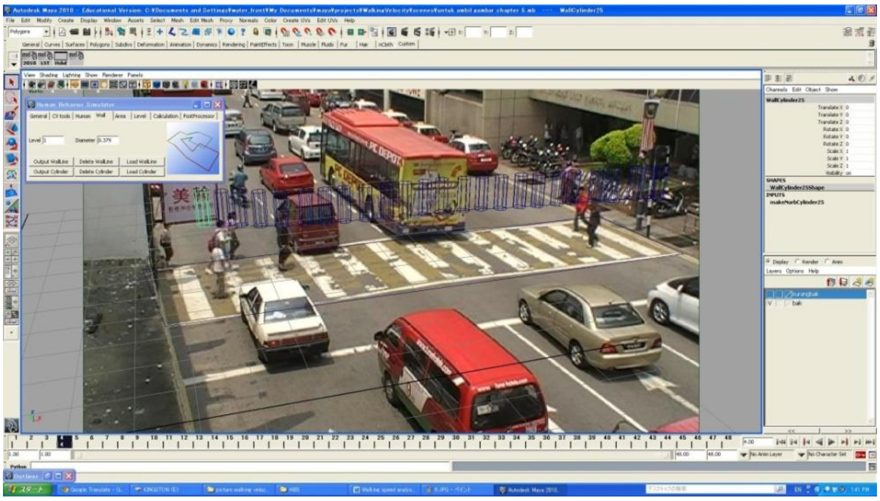


Fig. 3.7 (a) The track of pedestrian route is selected, **(b)** After select the route of pedestrian, the button <u>Output Cylinder</u> is click to obtain the coordinate *x*- and *y*- axis in each 0.5 second

Subsequently, the changes of pedestrian coordinate recorded in the "***.txt*** " file which allows to determine walking velocity. The velocity of pedestrian moving through a displacement (s) with a time interval (t) is described as follows:

$$v = \frac{s}{t} \tag{3.3}$$

The formula above described the velocity of pedestrian for the entire movement (walk) of pedestrian.

Regularly, when the walking velocity of pedestrian is examined at the walking facilities such as crosswalk or sidewalk, placing the masking tape was used as the mark to capture longitudinal pedestrian behavior. However, the interrupted pedestrian traffic flow is occurred especially during the peak time. Occasionally, the pedestrian had to slow down the walking velocity, stop for a while or change direction to avoid collisions with others. In that case, the movement of pedestrian is not in the straight line. Therefore, the distance of pedestrian route is inconsistent with the predetermined longitudinal distance. In order to disentangle the problem at disputed point, the equation is modified as follows:

$$\boldsymbol{v} = \lim_{\Delta t \to 0} \frac{s(t+\Delta t) - s(t)}{\Delta t} = \frac{ds}{dt} \tag{3.4}$$

The velocity vector $\boldsymbol{v}$ of the pedestrian has positions $s(t)$ at the time t and $s(t + \Delta t)$ at the time $t + \Delta t$ is the derivative of distance with respect to time. This equation has been used to determine the value of walking velocity of the Malaysia citizen. As explained at the beginning, the route of pedestrian is specified for every 0.5 second to reduce the error of displacement. The time interval is fixed value (0.5 second), while the distance displacement is variable.

At the same time, the age approximation and gender of each pedestrian should also be considered in this walking velocity analysis. During the age approximation (to the nearest decade), the best judgment for each pedestrian is analyzed in detailed. The age of pedestrian is estimated by observing walking attribute and human attire.

3.4.4 Analysis of Malaysian pedestrian walking velocity

The comprehensive objective of this research is to find out the value of average walking velocity for the Malaysian pedestrian. In this discussion some different of the average walking velocity are highlighted in relation to gender and age. From the conducted observation of pedestrian walking independently during pass through the crosswalk area, the average of walking velocity was extracted. **Table 3.2** to **Table 3.6** present the average, standard deviation and range of pedestrian walking velocity in unit of meter per second for children, adult and senior adult for different days during the peak time. Totally 1,092 pedestrians were observed.

From the presented results of **Table 3.2** to **Table 3.6**, the average walking velocity for the male adult pedestrian has the highest value of velocity with 1.38 m/s and the female senior adult has the lowest value with 1.04 m/s. While the average walking velocity of the female adult pedestrian is 1.20 m/s, male senior adult is 1.14m/s and children is 1.06 m/s. The comparison of average walking velocity differences between adult male and senior adult male, and between adult female and senior adult female were 0.24m/s and 0.16m/s respectively. This value indicates the reduction rate of walking velocity on the adult group to senior adult group, which is approximately identical for male and female. Besides, the standard deviation for each group was estimated at the lower average value. It represents the degree of data consistency and acceptance. The overall average walking velocity from the conducted observation is 1.16 m/s as shown in **Table 3.7**.

Table 3.2 Average walking velocity for the male adult group (10-39 years)

	N	Average	Standard deviation (m/s)	Range	
				Low	High
Day1	170	1.40	0.13	0.93	1.63
Day 2	110	1.39	0.16	0.87	1.73
Day 3	76	1.35	0.19	0.88	1.69
Average	-	1.38	0.16	-	-
Total	337	-	-	-	-

Table 3.3 Average walking velocity for the male senior adult group (40-69 years)

	N	Average	Standard deviation (m/s)	Range	
				Low	High
Day1	57	1.16	0.15	0.79	1.46
Day 2	81	1.10	0.13	0.88	1.40
Day 3	37	1.14	0.18	0.85	1.52
Average	-	1.14	0.15	-	-
Total	175	-	-	-	-

Table 3.4 Average walking velocity for the female adult group (10-39 years)

	N	Average	Standard deviation (m/s)	Range	
				Low	High
Day1	171	1.19	0.14	0.94	1.58
Day 2	125	1.19	0.15	0.93	1.66
Day 3	55	1.22	0.17	0.95	1.65
Average	-	1.20	0.15	-	-
Total	351	-	-	-	-

Table 3.5 Average walking velocity for the female senior adult group (40-69 years)

	N	Average	Standard deviation (m/s)	Range	
				Low	High
Day1	50	1.09	0.12	0.78	1.29
Day 2	58	1.03	0.10	0.78	1.27
Day 3	23	1.02	0.16	0.80	1.53
Average	-	1.04	0.13	-	-
Total	139	-	-	-	-

Table 3.6 Average walking velocity for the children group (5-9 years)

	N	Average	Standard deviation (m/s)	Range	
				Low	High
Day1	25	1.06	0.11	0.91	1.30
Day 2	35	1.02	0.17	0.72	1.34
Day 3	30	1.08	0.16	0.80	1.40
Average	-	1.06	0.15	-	-
Total	90	-	-	-	-

Table 3.7 Overall of average walking velocity for Malaysian pedestrian

	N	Average	Standard deviation (m/s)
L10-39	337	1.35	0.16
L40-69	175	1.14	0.15
P10-39	351	1.20	0.15
P40-69	139	1.04	0.13
Children	90	1.06	0.15
Average	-	1.16	0.15
Total	1092	-	-

3.4.5 Overall overview of walking velocity

Generally, the average walking velocity for different countries varies according to the environmental and cultural factors of those countries. Meanwhile, the average walking velocity with regards to the particular country will be affected by the individual age, gender, personal disabilities, and trip purpose. **Table 3.8** shows the list of average walking velocity in different countries. From the table, the continent of North America and Europe give high value of average walking velocity compared to Asia continent. This would be due to the difference in the physical build. And the socio-economic activities at the particular continent also will give significant influences. This can be proven through referring to the **Table 3.8**.

With reference to the finding of Malaysian average walking velocity observed in this study, it can be said that, the value (1.16m/s) is little lower in comparison to other Asian countries. In the case of neighboring country like Singapore, the value 1.23m/s and Thailand, with 1.22m/s. The Malaysian walking velocity is not far different with those countries.

Table 3.8 List of pedestrian average walking velocity (m/s) for different countries (Rahman *et al*., 2012 and Gotoh *et al*., 2009)

Continent	Country	Pedestrian average walking velocity (m/s)
Asia	Japan	1.12
	Saudi Arabia	1.08
	India	1.20
	China	1.20
	Bangladesh	1.20
	Thailand	1.22
	Singapore	1.23
	Sri Lanka	1.25
Europe	England(UK)	1.47
	Austria	1.54
North America	USA	1.47
	USA	1.35
	Canada	1.40

There are number of limitations in this measurement of walking velocity. First, the location of the observation should effect on the resultant walking velocity, also which might include the effect of the background of each pedestrian. Secondly, the time of observation needs to be considered either during weekdays or weekends, and/or during peak or non-peak hours. Other factors to be considered is the quality of video recorded for convenient of judgment of pedestrian attributes particularly age of pedestrian. The placement and the number of the video recorders will also influence on the recording the walking activities. The top view will give more information in relation to walking pattern besides velocity. And the more video recorders will give us more in-depth information.

The data of walking velocity is necessary and beneficial in terms of infrastructure design, health and safety purposes. Malaysian velocity acquired is quite similar with other Asian countries. Pedestrian of Malaysian have an average walking velocity of 1.16 m/s. Resultant data for velocities from the observation will be used in the pedestrian numerical studies.

3.5 Computer graphic model and input data

Under this sub section, basic description of methodology on how to create computer graphic of the study area and human model is deliberated. In this study, Autodesk® MAYA®2010 version (or in short MAYA) software is used in generating computer graphics of the study area and discloses the simulation results. The selection of MAYA is made based on the ability of MAYA to recognize visual workflow and it is equipped with a cross-platform scripting language, called Maya Embedded Language (MEL). MEL is provided for scripting and a means to customize the core functionality of the software, since many of the tools and

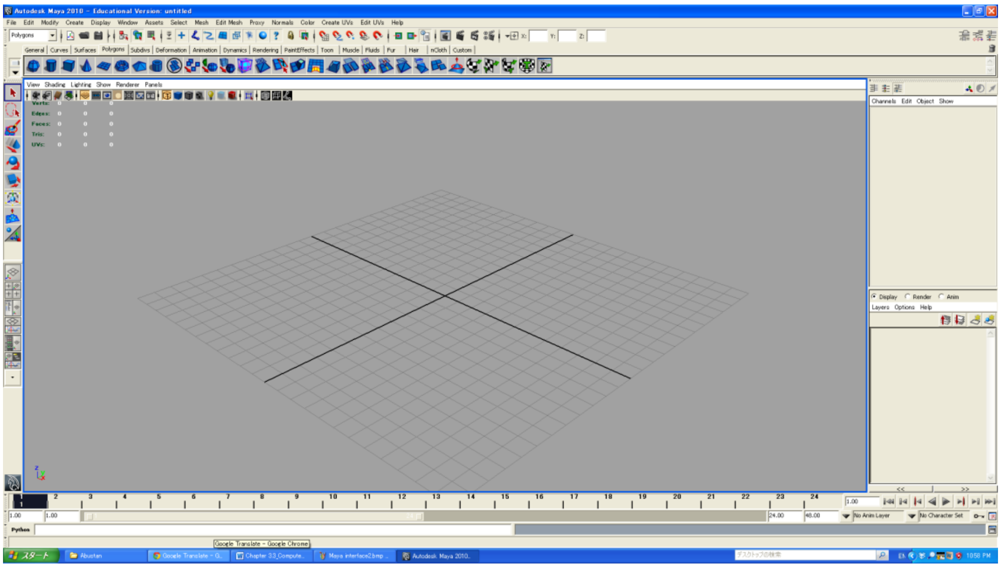


Fig. 3.8 Maya interface

commands used are written in it. Code can be used to plug-ins or be injected into runtime. Outside these superficial uses of the language, user interaction is recorded in MEL, allowing users to implement subroutines. Scene information can thus be dumped, extension file of .ma, editable outside MAYA in any text editor.

In this research a model represents a study area together with the actual land use of the study area and the position of the human. This representation is needed for considering evacuation planning because it is used to determine how to optimize a system, to predict performance, to enhance understanding of the system behavior and to examine worst-case scenario besides saving time and money.

3.5.1 Generate a Model

Typically in MAYA the user will interact with the interface as shown in **Fig. 3.8**. The MAYA workspace is where most of the work is conducted.

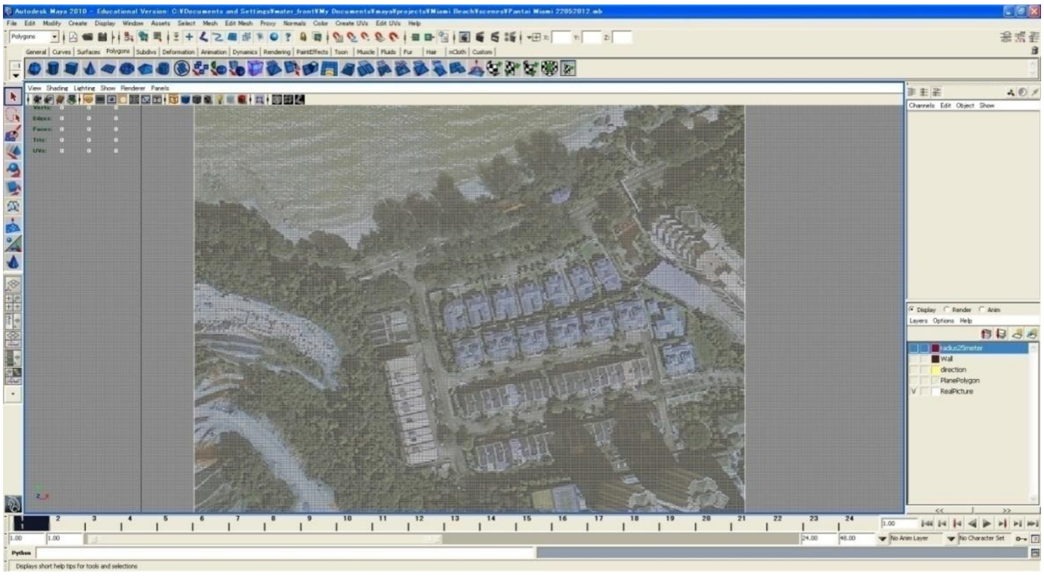
In order to generate a model, polygonal modeling process is applied where points in 3D space, called vertices, are connected by line segments to form a polygonal mesh. In MAYA modeling refers to the process creating virtual 3D surfaces for the characters and objects in the MAYA scene. Surfaces are vital for creating a convincing 3D image. To start modeling, a polygonal surfaces modeling technique is used. General procedures applied in this modeling work are listed below. However, the overall modeling works are not only limited to the listed procedures here. More virtual skills and mastery of the modeling tools are also required.

1. 2D images plane is used as a reference for constructing 3D model;
2. 3D primitives are used as the basis to creating more complex 3D model;
3. Components of a polygon mesh (faces, edges, and vertices) are worked with;
4. Polygon faces are created by placing vertices;
5. Faces on a polygon mesh are scaled and extruded;
6. Extruded polygonal meshes moved and rotated;

7. Vertices split and polygonal faces subdivided;
8. Separate meshes combined into one mesh;
9. Faces added to an existing mesh;
10. Snap to Grid is used.

Fig. 3.9 (a) and **(b)** are the 2D images plane used in this research. The 2D images planes are representing the two study areas, which are the Miami Beach image and the Teluk Batik Beach image respectively.

a)



b)

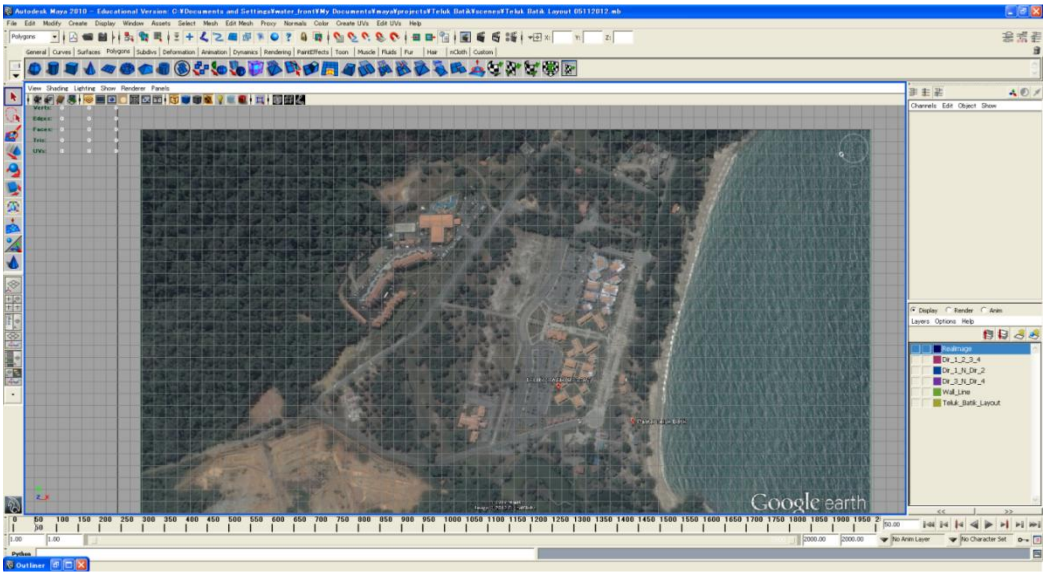


Fig. 3.9 (a) The Miami Beach 2D Image; **(b)** The Teluk Batik Beach 2D Image

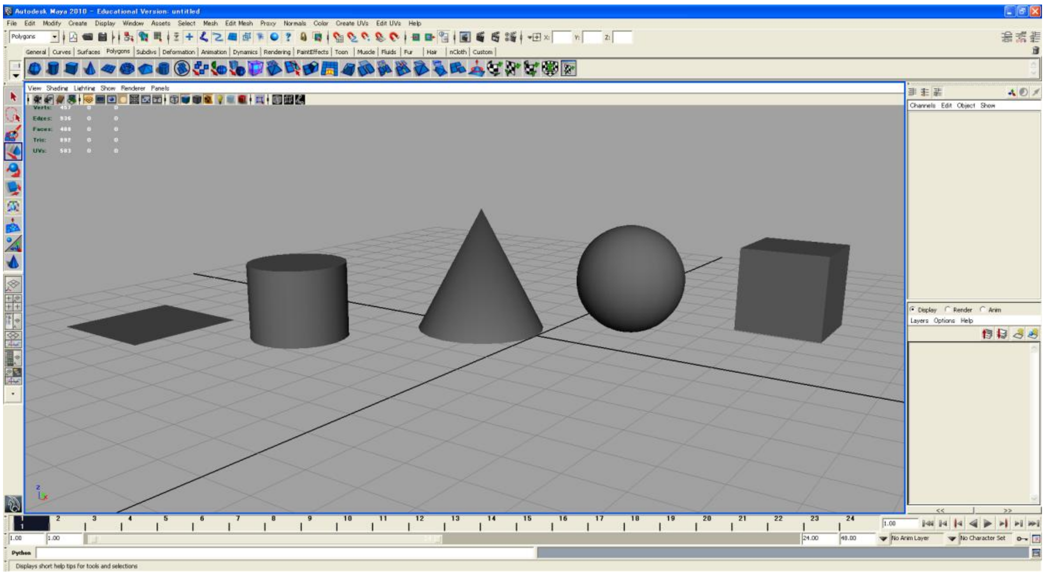


Fig. 3.10 The 3D Primitives; Plane, Cylinder, Cone, Sphere and Cube

Fig. 3.10 shows common 3D primitives used in this modeling work. The 3D primitives are actually basic geometric shapes that being used in conjunction to create complex 3D models like attributes of the study areas' environment and detailing works of site.

Once the polygonal meshes are done, rendering process is applied. In MAYA, rendering refers to the process of creating bitmap images of the scene based on the various shading, lighting, and camera attributes that being set. When rendering, MAYA takes into account all of the various objects and scene attributes, and performs mathematical calculations to produce the final image or image sequence. Once a sequence of images is rendered, movie can be produced by play them back. Rendering involves many components to produce an image:

1. Shading materials and textures
2. Lighting and shadows
3. Cameras and movie
4. Rendering method
5. Visual effects

The final stage in MAYA is creating a movie. This process is more towards the reproduction of the evacuation process. The movie procedure is discussed further in the future sub topic (reproduction of evacuation process).

3.5.2 Input data

This sub section explained the methodology that will follow in order to apply the Human Behavior Simulator (HBS) tool in conjunction to data input of pedestrian's attributes and model's characteristics. Through scripting language of MEL, HBS tool was developed and plugged-in in MAYA software. By doing this, certain tasks that are not available from the MAYA's GUI can be achieved.

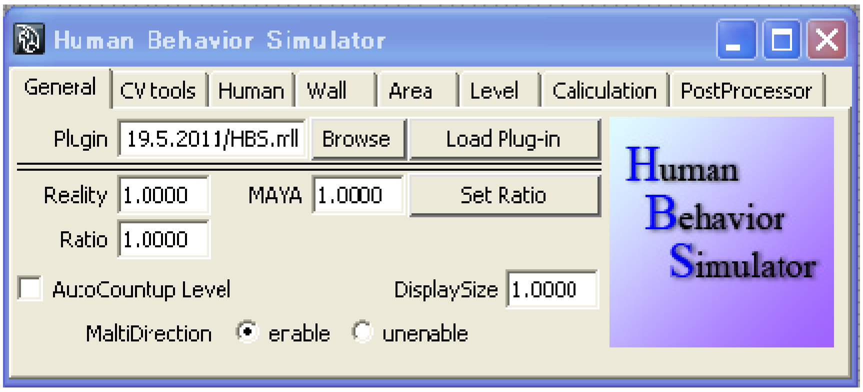


Fig. 3.11 HBS Interface – General menu

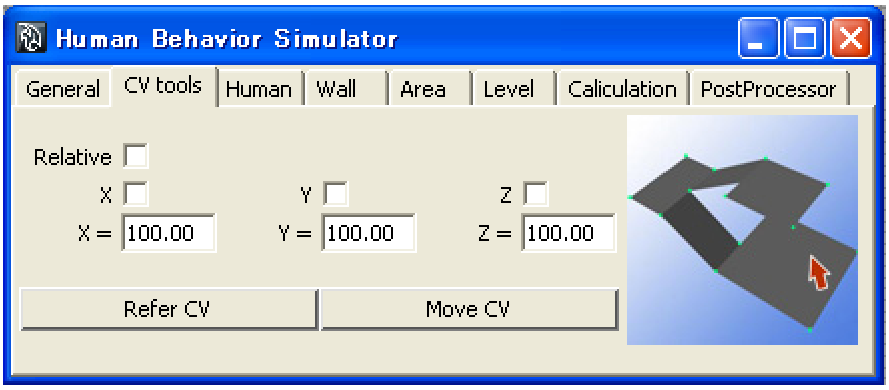


Fig. 3.12 HBS Interface – CV tools menu

The HBS's interface is as shown in **Fig. 3.11** below. The Main Menu Bar appears at the top of the HBS's interface. At Main Menu Bar, it displays of eight menu sets including General menu, CV tool menu, Human menu, Wall menu, Area menu, Level menu, Calculation menu and PostProcessor menu. Each menu corresponds to particular application in data input.

The General menu (**Fig. 3.11**) is a menu where the HBS tool is set to be used and the initial condition of the modeling work is established. To generate the tool, from the Plugin item the HBS.mll file is browsed. Load Plug-in button is then pressed and immediately the HBS tool is already activated. The initial condition of the modeling involve in this tool are the scale of the study area's model between actual study area and in MAYA and also the condition of the direction of the pedestrian either one direction or multi directions.

In doing so, the ratio between reality and MAYA is determined based on own calculation and the ratio's value is inserted in the Ratio box displayed. The MultiDirection is selected enable if the direction of the pedestrian movement is multidirectional and vice versa if considered unidirectional movement. At the moment, the items for AutoCountup Level and DisplaySize are set unchecked and 1.0000, respectively.

For the CV tools menu as shown in **Fig. 3.12**, the coordinates of vertices (in MAYA workspace) in *x*-, *y*- and *z*- direction can be obtained by selecting Refer CV button. Besides, the vertices also can be moved to a particular coordinate by assigning the values corresponds to the checked boxes either X or Y or Z and pressing the Move CV button in final. The Relative item is left unchecked.

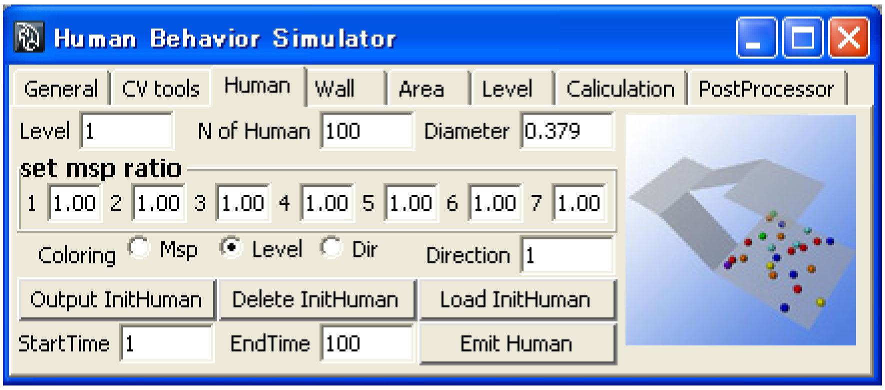


Fig. 3.13 HBS Interface – Human menu

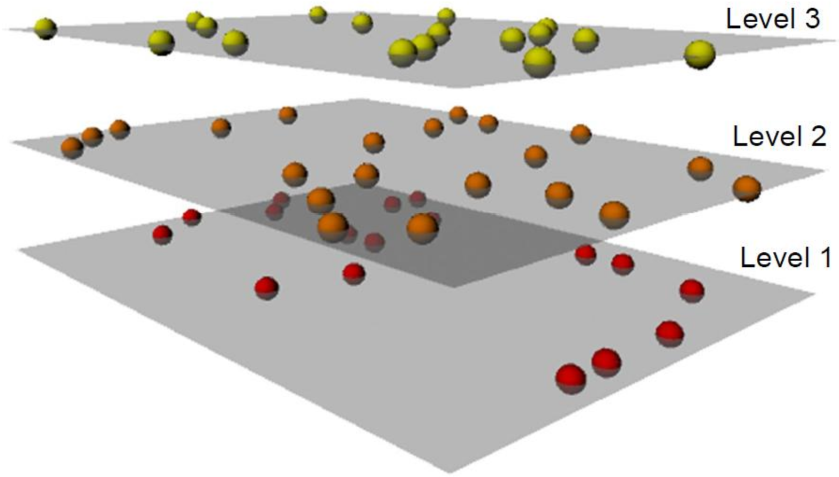


Fig. 3.14 Pedestrians position corresponds to level

The rest of the menus are related to the data input of the simulation condition. Starting with Human menu (**Fig. 3.13**), pedestrian's attributes are set concisely. In this menu, five rows are displayed. Each row is briefly explained below:

1. The first row – consists of three items: Level item, N of Human item and Diameter item. The Level item is set to 1. The Level item is referring to pedestrian position in the study area corresponds to the defined level number of the area. This is shown diagrammatically in **Fig. 3.14** below. The N of Human item is related to the number of pedestrians considered in the simulation. This is done by inserting the values in the box provided. The Diameter item is referring to human diameter and is set to 0.379.

2. The second row – the MSP ratio is set in the boxes provided. The MSP ratio is corresponding to the seven classes of human that have been determined during population distribution data taken.
3. The third row – consist of Coloring item. This is related to the color to be appeared in the model which is corresponded to the checked item either Msp or Level or Dir. This tool is applicable when references are to be made according to the human classes or human position or human direction. In this row also, the Direction item is displayed on the far right. The item is referring to the direction of the human. This is directly related to the selected MultiDirection performed in the General menu.

4. The fourth row – there are three buttons namely Output InitHuman, Delete InitHuman and Load InitHuman. When pressing the Output InitHuman button together with the selected area from the model in MAYA workspace, the number of pedestrians set in N of Human item is loaded. The Delete InitHuman button is for deleting the pedestrians appeared. And the last button Load InitHuman is to reload the initial pedestrian position set in the Output InitHuman.
5. The fifth row – which consists of StartTime, EndTime and Emit Human button are only used to placing the pedestrians which emit from one certain range of time.

The next menu, Wall menu (as shown in **Fig. 3.15**) is used to set the virtual wall of the study area. In this menu, Level item is similar to the definition in Human menu and Diameter item is fixing to 0.379. In this study only the first three buttons are used. The procedure of assigning Output WallLine, Delete WallLine and Load WallLine buttons is similar in Human menu as described for the fourth row.

The Area menu (**Fig. 3.16**) is used to define the direction of the pedestrians on particular areas. By selecting faces and curves, the Output Area button is pressed then. The Delete Area and Load Area buttons are similar to the previous procedure in Human and Wall menus. In this menu too, the Goal item need to be set. This item is referring to final destination of each pedestrian. The Slope item is related to reduction of movement speed in selected areas. The Direction Number item is related to direction assigned previously in Human menu. The last item used is Edit Area menu which is used to edit if there amendment made to Level, Goal, Slope and Delete.

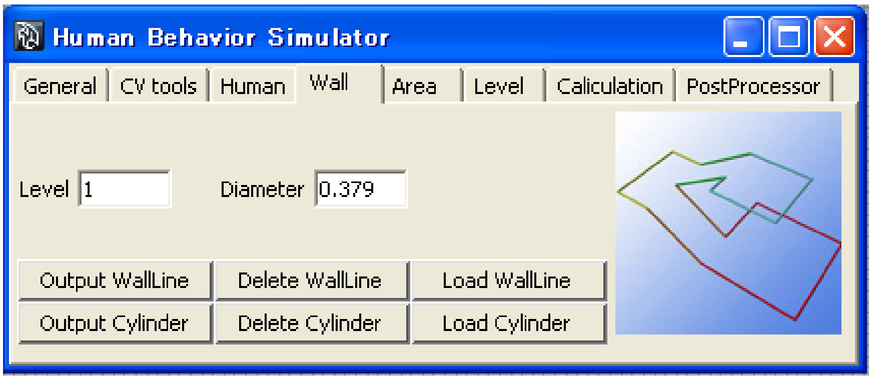


Fig. 3.15 HBS Interface – Wall menu

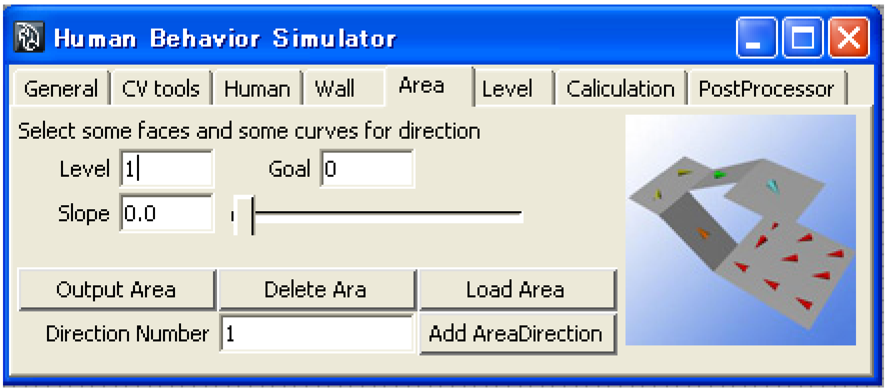


Fig. 3.16 HBS Interface – Area menu

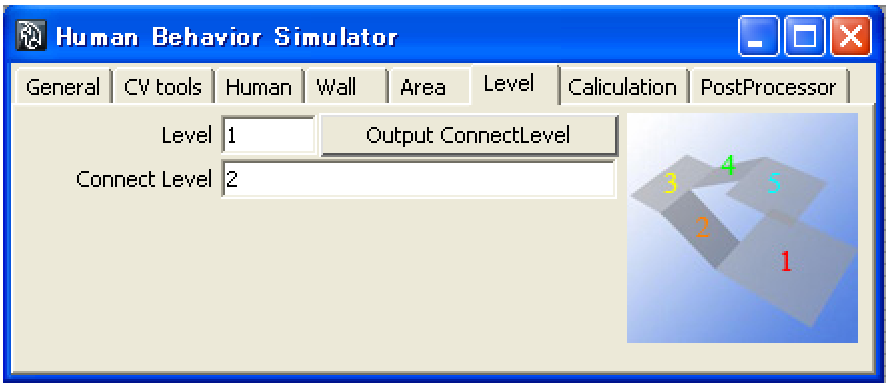


Fig. 3.17 HBS Interface – Level menu

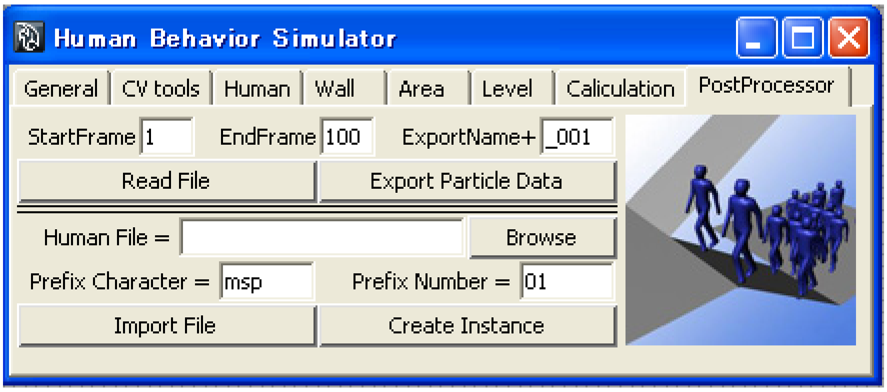


Fig. 3.18 HBS Interface – PostProcessor menu

The next menu which is Level menu (**Fig. 3.17**) is to assign from one level to one level. And the last menu – PostProcessor menu (**Fig. 3.18**) is to read the snap file in order to display the pedestrian movement after the simulation calculation is completed. From the beginning of the setting work, the pedestrians are assigned as spheres. To change the spheres to human kind the animated human file is browsed by pressing Browse button. In order to load the file, the Import File button is pressed.

3.6 Numerical simulation

Numerical simulation is a set of numerical methods to solve a set of ordinary differential equation. There exist several methods with a combination of various mathematical models. The movement of pedestrians on the crowded circumstances is perceived as ensemble of particles that move with external forces. This scenario poses the similarity as well as in sediment transport process. Consequently, numerical model that have been established by the previous research on sediment transport processes using the DEM has been adapted (e.g., Gotoh and Sakai (1997); Harada and Gotoh (2008)).

The original of CBS-DE was developed in the year of 2004 by Gotoh *et al.* to evaluate the evacuation process against tsunami event. Subsequently, in 2012 the improvement of CBS-DE has been made by considering the effect of alignment and evasive action. In the following section, mathematical equation involved in CBS-DE and CBS-DE with self-evasive simulator is explained.

3.6.1 Crowed behavior simulator of disaster evacuation (CBS-DE)

3.6.1.1 Fundamental equations

In this section, the CBS-DE model (Gotoh *et al*., 2012) is outlined. The equation of motion for simulating each individual behavior which consists of translational and rotational equations are given as follows:

$$m_{hi}\dot{\boldsymbol{v}}_i = \mathbf{F}_{mi} + \mathbf{F}_{ci} \tag{3.5}$$

$$I_{hi}\dot{\boldsymbol{\omega}}_i = \mathbf{T}_i \tag{3.6}$$

where m_{hi} is the mass of the person i, $\boldsymbol{v}_i$ is the velocity of the person i, " • " indicates a time-derivative, $\mathbf{F}_{mi}$ is the autonomous driving force of the person i, $\mathbf{F}_{ci}$ is the interacting force acting on the person i, I_{hi} is the moment of inertia of the person i, $\boldsymbol{\omega}_i$ is the angular velocity of the person i, $\mathbf{T}_i$ is the torque acting on the person i. For simplicity, the each person is representing as a cylinder element with diameter, d_{hi}. Therefore, the mass and the moment of inertia of the person i can be written as:

$$m_{hi} = \varepsilon_{hi}\sigma_{hi}B_{hi}\frac{\pi d_{hi}^{\ 2}}{4} \quad ; \quad I_{hi} = \varepsilon_{hi}\sigma_{hi}B_{hi}\frac{\pi d_{hi}^{\ 4}}{32} \tag{3.7}$$

where σ_{hi} is the density of the person i, B_{hi} is the body height of the person i, ε_{hi} is the correction coefficient concerning the volumetric difference between the cylinder element and the actual person. In order to solve the above equation, the following value are assign to be used as parameter; d_{hi} = 0.379 m, ε_{hi} = 0.15, σ_{hi} = 980 kg/m^3, B_{hi} = 1.6 m. In the numerical simulation, a positional vector, a velocity vector and an angular velocity are updated explicitly by an Eulerian explicit scheme and the time integration scheme is determined with consideration of numerical stability and accuracy.

3.6.1.2 Autonomous driving force

Each person is characterized by his or her free equilibrium walking velocity, v_{limit}. It is assumed that the isolated person is accelerated until they achieve the comfortable walking speed. The autonomous driving force $\mathbf{F}_{mi}$ terms are:

$$\mathbf{F}_{mi} = m_i\mathbf{a} \tag{3.8}$$

where **a** is the acceleration vector. The equilibrium walking velocity is being affected by number density of human. Therefore, the magnitude of the maximum equilibrium walking velocity v_{max} is given as follows:

$$v_{max} = v_{limit} - \gamma \cdot c_k \tag{3.9}$$

where γ is the proportional coefficient depend on the congestion condition in designated area, c_k is the number density of persons inside the psychological perception area (see **Fig. 3.16**). To perform satisfactory crowd simulation, we classified the human into 7 categories by gender and age group.

3.6.1.3 Interacting forces

The person's visual perception is represented as illustrated in **Fig. 3.19**. Each individual person is controlled by the perception domain as illustrated in **Fig. 3.19**. Concerning the physical repulsive force, the following equations are the critical conditions.

$$\left|\mathbf{r}_i - \mathbf{r}_j\right| \le \frac{d_{hi} + d_{hj}}{2} \quad ; \quad \left|\mathbf{r}_i - \mathbf{r}_W\right| \le \frac{d_{hi} + d_W}{2} \tag{3.10}$$

where $\mathbf{r}_i$ denotes the positional vector of the person i, $\mathbf{r}_W$ is the positional vector of the virtual wall element W, $\mathbf{r}_i$ is the diameter of the virtual wall element W. While, the psychological repulsive force acts when two adjacent persons i and j satisfy the following condition:

$$\left|\mathbf{r}_i - \mathbf{r}_j\right| \le \mathit{\Lambda} \tag{3.11}$$

where $\mathit{\Lambda}$ represent the psychological radius.

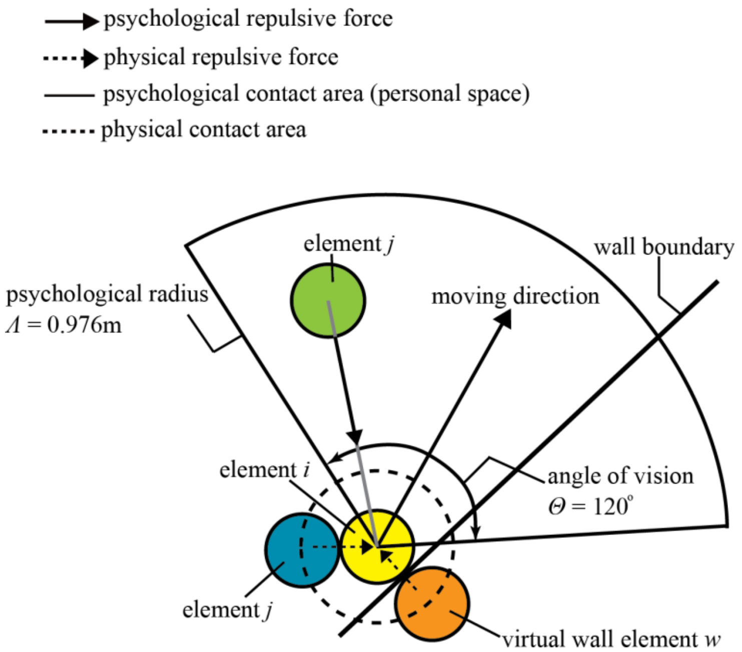


Fig. 3.19 Schematic overview of physical- and psychological-contact model

The total interacting force acting on the person i is described as follows:

$$\mathbf{F}_{ci} = \mathbf{F}_{d(p/p)i} + \mathbf{F}_{d(W/p)i} + \mathbf{F}_{ps\_i} \tag{3.12}$$

where $\mathbf{F}_{d(p/p)i}$ is the physical repulsive force acting on the person i, $\mathbf{F}_{d(W/p)i}$ is the physical repulsive force between the virtual wall element W and the person i, $\mathbf{F}_{ps\_i}$ is the psychological repulsive force acting on the person i.

$$\mathbf{F}_{d(p/p)i} = \sum_{j(\neq i)} \mathbf{f}_{ij} \;\; ; \;\; \mathbf{F}_{d(W/p)i} = \sum_{W} \mathbf{f}_{iW} \;\; ; \;\; \mathbf{F}_{ps\_i} = \sum_{j(\neq i)} \mathbf{f}_{ps\_ij} \tag{3.13}$$

$$\mathbf{T}_i = \frac{1}{2}\left\{ \sum_{j(\neq i)} (\mathbf{r}_j - \mathbf{r}_i) \times \mathbf{f}_{ij} + \sum_{W} (\mathbf{r}_W - \mathbf{r}_i) \times \mathbf{f}_{iW} \right\} \tag{3.14}$$

where $\mathbf{F}_{d(p/p)i}$ denotes physical repulsive force acting on the person i, $\mathbf{F}_{d(W/p)i}$ denotes the physical repulsive force between the virtual wall element W and the person i, $\mathbf{F}_{ps\_i}$ denotes the psychological repulsive force acting on the person i, $\mathbf{f}_{ij}$ denotes the local physical repulsive force between the persons i and j, $\mathbf{f}_{iW}$ denotes the local physical repulsive force between the person i and the virtual wall element W, $\mathbf{f}_{ps\_ij}$ denotes the local psychological repulsive force between the persons i and j.

These local repulsive forces $\mathbf{f}_{ij}$, $\mathbf{f}_{iW}$ and $\mathbf{f}_{ps\_ij}$ are given as follows:

$$\left.\begin{aligned} &\mathbf{f}_{com.} = \left[\frac{(\mathbf{e}^n)^{pre} + k^n \Delta r^n \mathbf{n}}{\mathbf{e}^n} + \frac{c^n \Delta v^n \mathbf{n}}{\mathbf{d}^n} \right]_{com.} + \left[\frac{(\mathbf{e}^t)^{pre} + k^t \Delta r^t \mathbf{t}}{\mathbf{e}^t} + \frac{c^t \Delta v^n \mathbf{t}}{\mathbf{d}^n} \right]_{com.} = \mathbf{f}^n + \mathbf{f}^t \\ &\mathbf{f}^n = \mathbf{e}^n + \mathbf{d}^n \, ; \mathbf{f}^t = \mathbf{e}^t + \mathbf{d}^t \end{aligned}\right\} \tag{3.15}$$

$$\left.\begin{aligned} &\Delta r^n = \left[\mathbf{r}_{target} - \mathbf{r}_i\right]_{\Delta t} \cdot \mathbf{n} \, ; \quad \Delta r^t = \left[\mathbf{r}_{target} - \mathbf{r}_i\right]_{\Delta t} \cdot \mathbf{t} \\ &d = \left|\mathbf{r}_i - \mathbf{r}_{target}\right| \\ &\boldsymbol{n} = \left(\mathbf{r}_i - \mathbf{r}_{target}\right)/d = \left(n^1, n^2\right); \quad \mathbf{t} = \left(-n^2, n^1\right) \\ &\Delta v^n = \left[\mathbf{v}_{target} - \mathbf{v}_i\right] \cdot \mathbf{n} \, ; \quad \Delta v^t = \left[\mathbf{v}_{target} - \mathbf{v}_i\right] \cdot \mathbf{t} \end{aligned}\right\} \tag{3.16}$$

where $\mathbf{e}^n$ and $\mathbf{e}^t$ are the component of the repulsive force due to the elastic springs, k^n and k^t denotes the spring constants in the normal and the tangential directions, respectively, $\mathbf{d}^n$ and $\mathbf{d}^t$ denotes the repulsive force due to the viscosity dashpots, c^n and c^t denotes the dashpot constants in the normal and tangential directions, respectively, $\mathbf{f}^n$ and $\mathbf{f}^t$ are the total repulsive force in the normal and tangential directions, respectively. The superscript "*pre*" indicates the previous numerical time step, $\mathbf{r}_{target}$ represents the positional vector of the target element. Subscript "*com.*" indicates ij, iW and ps_ij, and the corresponding the subscript "*target*" are the person j and the virtual wall element W.

In the present simulation, a special attractive force between flocks, such as a family, friends and a couple is not considered. To simulate a flock behavior, a psychological attractive force between persons should be incorporated. Here, it is assumed that each person walks independently without any special psychological attractive force. Hence the joint without resistance against tensile force is allocated in the normal direction as follows:

$$\mathbf{f}_{com.} = 0.0 \textit{ then } \mathbf{e}^n < 0.0 \tag{3.17}$$

Meanwhile, the frictional force works in the tangential direction as follows:

$$|\mathbf{e}^t| > \mu\mathbf{e}^n \text{ then } \mathbf{f}^t = \mu \cdot \text{SIGN}(\mathbf{e}^n, \mathbf{e}^t) \tag{3.18}$$

$$\text{SIGN}(a,b) = \begin{cases} |a| \textit{ when} b \geq 0 \\ -|a| \textit{ when } b<0 \end{cases} \tag{3.19}$$

where μ is the frictional coefficient at the contact point.

3.6.2 Crowded behavior simulator of disaster evacuation (CBS-DE) with self-evasive action

Based on the observation during high density of pedestrian in contraflow, the pedestrian has an inclination to follow the front pedestrian in the same direction to avoid collision with other pedestrian. Consequently, lane formation phenomena are produced and such formation enables smooth movement even in high-density state. Here, behaviors of collision avoidance and an alignment are described by a single model introducing the self-evasive force, since both actions are closely related in each other. Self-evasive force is combining together with autonomous driving force and interacting force make three component forces existed in translational equation.

The self-evasive force is estimated by referring to the predicted position of surrounding pedestrians after Δt_f seconds as shown in **Fig. 3.20**.

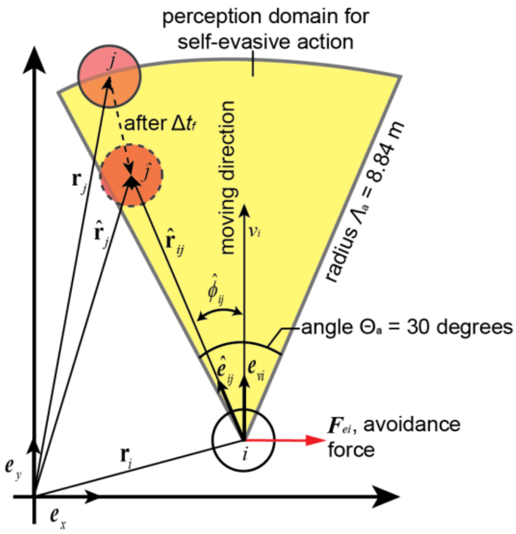


Fig. 3.20 Perception domain for self-evasive action

Based on observation by Tatabe et al. (1994), the turning angle to avoid the static obstacle is $\Theta_a = \pm 15^o$ and the radius of the perception domain for self-evasive action is Λ_a = 8.84m. The self-evasive force is described as follows:

$$\mathbf{F}_{ei} = \begin{cases} m_i \sum_{j(\neq i)}^{N_k} \kappa \frac{(\mathbf{v}_i - \mathbf{v}_j)\cdot \mathbf{e}_{vi}}{\Delta t_f} (\hat{\mathbf{e}}_{ij} \times \mathbf{e}_{vi}) \times \mathbf{e}_{vi} & when\ \hat{\mathbf{e}}_{ij} \times \mathbf{e}_{vi} \neq \mathbf{0} \\ m_i \sum_{j(\neq i)}^{N_k} \kappa \frac{(\mathbf{v}_i - \mathbf{v}_j)\cdot \mathbf{e}_{vi}}{\Delta t_f} (\mathbf{e}_x \times \mathbf{e}_y) \times \mathbf{e}_{vi} & when\ \hat{\mathbf{e}}_{ij} \times \mathbf{e}_{vi} = \mathbf{0} \end{cases} \tag{3.20}$$

$$\kappa = \alpha \frac{\cos\hat{\phi}_{ij}}{|\hat{\mathbf{r}}_{ij}| / r_v}; \quad \cos\hat{\phi}_{ij} = \mathbf{e}_{vi} \cdot \hat{\mathbf{e}}_{ij} \tag{3.21}$$

$$\hat{\mathbf{r}}_{ji} = \hat{\mathbf{r}}_j - \mathbf{r}_i; \quad \hat{\mathbf{r}}_j = \mathbf{r}_j + \mathbf{v}_j \Delta t_f \tag{3.22}$$

where $\boldsymbol{N_k}$ is the total number of pedestrian in the perception domain of self-evasive action, Δt_f is the time for the self-evasive action, $\mathbf{e}_{vi}$ is the unit vector in the $\mathbf{v}_i$ direction, $\hat{\mathbf{e}}_{ij}$ is the unit vector in the $\hat{\mathbf{r}}_{ji}$ direction, $\mathbf{e}_x$ and $\mathbf{e}_y$ is the unit vector in the *x*- and *y*- axis, respectively, α is the proportional coefficient, $\hat{\mathbf{r}}_j$ is the predicted positional vector of the pedestrian *j* after Δt_f. Eq. (3.20) indicates that in the case of increase in relative traveling velocity between the pedestrians *i* and *j*, the avoidance force acts on the pedestrians *i*, meanwhile, the alignment force acts on the pedestrian *i* in the case of decrease in relative velocity between the pedestrians *i* and *j*. As for the singularity treatment, when the unit vector $\hat{\mathbf{e}}_{ij}$ equals with the unit vector $\mathbf{e}_{vi}$ the avoidance force $\mathbf{F}_{ei}$ acts on pedestrian *i* in the right direction perpendicular to the travelling direction of the pedestrian *i*.

3.6.3 Model constants

Setup procedure of model constants shown in **Table 3.9** is employed with referring to Kiyono *et al*. (1998). According to this procedure, all of constants for spring and dashpot are determined automatically by giving a normal spring constant, k^n. The physical normal spring constant k^n (=1.26×10^4 N/m), which was measured with compressing actual human body, is used. Otherwise, the psychological normal spring constant k^n between persons is determined by setting autonomous driving force so as to be equal to the normal component of the psychological force under the minimum psychological distance between pedestrians. And, the relation between spring and dashpot constants is set to satisfy the critical damping condition of the Voigt model in a single degree of freedom. And the tangential spring constant is given as 0.05 times as much as the normal spring constant.

Table 3.9 Setup procedure of model constants between persons

		Physical repulsive force, *ij*	Psychological repulsive force, *ps_ij*
spring	k^n	k^n= 1.26×10^4 N/m	$k^n = \frac{\mathrm{Ma}}{\Lambda - \frac{\mathrm{d}}{2}}$
	k^t	k^n×0.05	k^n×0.05
dashpot	c^n	$2(\mathrm{M}k^n)^{1/2}$	$2(\mathrm{M}k^n)^{1/2}$
	c^t	$2(\mathrm{M}k^n)^{1/2}$×0.05	$2(\mathrm{M}k^n)^{1/2}$×0.05

3.7 Reproduction of evacuation process

Reproduction of the details of the evacuation process can be directly investigated with CG movie. In this stage, the visualization of the evacuation process is performed. It is used to educate people and understand the behavior of the evacuation process. **Fig. 3.21** below shows example of typical snapshots.

(a)

(b)

Fig. 3.21 Typical snapshots of evacuation process; **(a)** the Miami Beach; **(b)** the Teluk Batik Beach

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CHAPTER 4
NUMERICAL SIMULATION FOR EVACUATION PLANNING AT THE MIAMI BEACH, PENANG, MALAYSIA

4.1 Introduction

The 2004 Indian Ocean tsunami caused loss of lives and damages to property in Malaysia. In Malaysia three main areas lying along the coastal belt were affected. Penang Island was one of the worst areas hit by the said tsunami. Lack of early warning system will be considered as the current problem when the tsunami comes to coastal areas in Penang Island. In case of the 2004 Indian Ocean Tsunami, the first wave landed in three hours then it struck Banda Aceh, Sumatra in the morning. In Penang Island, there were two beaches that heavily affected by the tsunami; the Bayu Senja Beach and the Miami Beach. Both beaches normally receive many visitors throughout the years particularly during a long weekend either by local or international tourists. These areas become the main attraction due to their beauty and clean beaches in which facing the Andaman Sea.

The unprecedented tragedy clearly underscored the need for placing a proper system of tsunami evacuation planning toward a quick evacuation from vulnerable coastal communities to safer areas. Accordingly this chapter discusses the numerical simulation of crowd behavior in order to investigate detailed evacuation process for the Miami Beach, Penang Island, Malaysia. The discussion documented about evacuation planning through qualitative and quantitative analysis by using CBS-DE simulator. The sequential procedures of study on evacuation planning are shown specifically starting from general background of the study area, and then, input data of simulation, investigation of present condition of evacuation process at the Miami Beach, and improvements of evacuation planning to the present condition.

4.2 General background

The number of casualties stands at 68 persons in Malaysia during the said tragedy. And by the majority coming from Penang was 52 persons. **Table 4.1** shows the statistics of lost and injured life in district in Penang during 2004 tsunami hit.

The Miami Beach is arguably the popular destination on Penang Island where local and foreign tourist visit. The fantastic scenery of the Andaman Sea seemingly spared from natural disasters, and this beach receiving thousands of tourists every year will owe to such a coast having the fantastic scene. However, the tsunami on 26 December 2004, which brought devastated condition around the Penang Island coastline including the Miami Beach, changed the perception. The Miami Beach recorded a large number of casualties with more than five fatalities. All of them were tourists who are picnicker and the high statistic numbers of casualties recorded in this area was children.

From the site interviews conducted, there would be three dominated factors that reasons why the fatality cases happen; (1) lack of awareness; (2) inadequacy of access road; and (3) lack of early warning system. One way for mitigating potential of the loss for lives from a similar event in the future is to improve the safety of visitors (either local communities or tourists). The countermeasures need to be prepared for facing the unpredicted event in near future by installing an early warning system for tsunami, providing adequate access roads, and establish the evacuation planning.

Meanwhile, through observational study, there were no proper access roads at the Miami Beach which allow the visitors to use or evacuate in the event of mishap. Before the tsunami event, only two access paths available were used either to enter or exit the beach. This was one of the difficulties for visitors to escape from the beach during any disaster events. On top of that, due to crop rocks around the beach, add more difficulties to the visitors to escape. **Photo 4.1** shows the view of the Miami Beach.

Table 4.1 Statistics of lost and injured life in district in Penang

Incident	Deaths	Injured
Batu Feringghi , Tanjung Tokong	**19**	**92**
Telok Bahang, Pulau Betong	16	90
Jalan Padang Benggali , Teluk Air Tawar	2	19
Total	52	206

Photo 4.1 View of Miami Beach

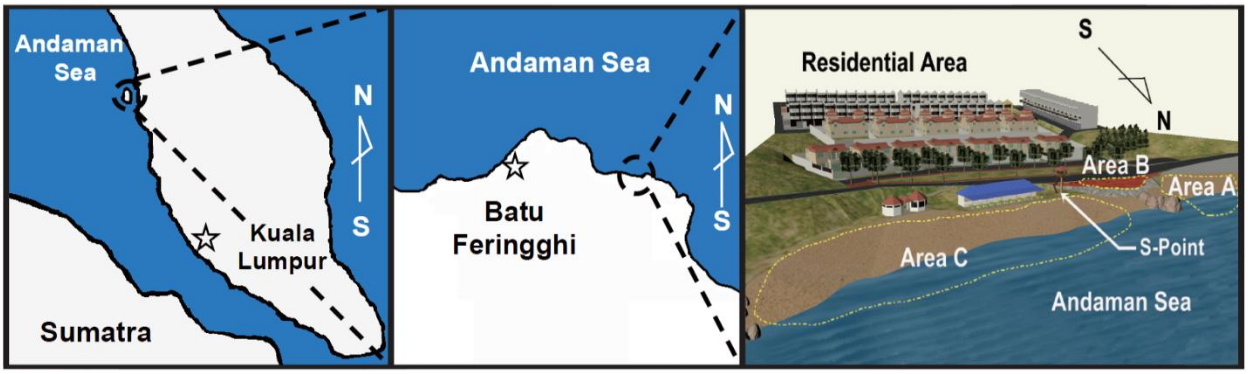


Fig. 4.1 Bird's eye view of target domain for evacuation planning

Promptly additional and new access paths have been built after the tragedy. By improving the access path, the visitors from east side of shore can escape easily if any unexpected disasters happened. It can reduce the evacuation time at the same time. However, the proper evacuation plan has not been developed yet. The proper evacuation plan will smoothly lead visitors to the safe areas during the emergency event.

4.3 Input data of simulation

One essential pre-requisite in planning the evacuation is collecting the exact data of the study area and population distribution. The Miami Beach of Penang Island is selected as the site of the present study. The length of shoreline is approximately 270 meters and the width is about 30 meters. The rocky promontory on both ends of the Miami Beach shoreline separates the area from the nearby coast and forms the gulf. The colossal boulder rock formation at the central coast of the beach area is divided into two parts. **Fig. 4.1** shows the computational domain of the study which is illustrated by a bird's-eye view. The Miami Beach is located in sea-front delta with a hill on its back. The hill has an approximately 23 meters in height above the sea level. And this height is considered as adequate level of setting an evacuation place against tsunami.

The field survey for the distribution of the population was conducted with the cooperation by a group of researchers from Universiti Sains Malaysia (USM), Malaysia. The population distribution survey was conducted for four days: on 17th, 18th, 24th and 25th of April 2010 (during weekends). The counting number of visitors through the day for every hour, starting from 9.00 am to 7.00 pm. **Table 4.2** shows the distribution of population observed by field survey in the Miami Beach at a peak time. In the present study, the population is classified into seven categories by gender and age group. In this case study, the average walking velocity of Malaysian pedestrian (as can be referred in **Table 4.2**) was imposed. The average walking velocity of Malaysian pedestrian is based on the analysis of the observation conducted at Penang during the author's Internship program in 2011. The detailed procedure of average walking velocity analysis for Malaysian pedestrian was discussed in the Chapter 3. The average walking velocities are used in evaluating the evacuation planning process to demonstrate the effect of different velocity value on the evacuation process. Most of visitors were between the age of 10 and 39 years for both male and female.

In this study, persons are initially arranged randomly in the computational domain which has been divided in three areas, namely Area **A**, **B**, and **C**, as illustrated in **Fig. 4.1**. However, the numbers of population for each area specified was obtained from the field observation. And the population in each area specified according to the human type is shown in **Fig. 4.2**. The initial arrangements of the persons are assigned randomly around the beach area as shown in **Fig. 4.3**. All cases used the same initial arrangement. Each simulation was the specified by the moving direction of persons.

In the present simulation, the completion of evacuation is assumed that all people reach at altitude of more than 7 meters above the sea level, which is based on the observed tsunami record in 2004. The assumption were made that the condition of the warning device breaks down and people begin an evacuation process after receiving the verbal evacuation signal propagated concentrically from the S-point shown in **Fig. 4.1**. And the speed of the propagation of the evacuation signal is set as 1.5m/s.

Table 4.2 Distribution of population observed during field survey in the Miami Beach (Peak time)

Human type	**Sex**	**Age**	**People**	**Ratio (%)**	**Velocity (m/s)**
1	Male	10-39	93	27.93	**1.38**
2	Male	40-69	53	15.92	**1.14**
3	Male	Over 70	4	1.20	**0.99**
4	Female	10-39	93	27.93	**1.20**
5	Female	40-69	41	12.31	**1.04**
6	Female	Over 70	3	0.90	**0.89**
7	Child	5-9	46	13.81	**1.06**
		Total	**333**	**100 %**	

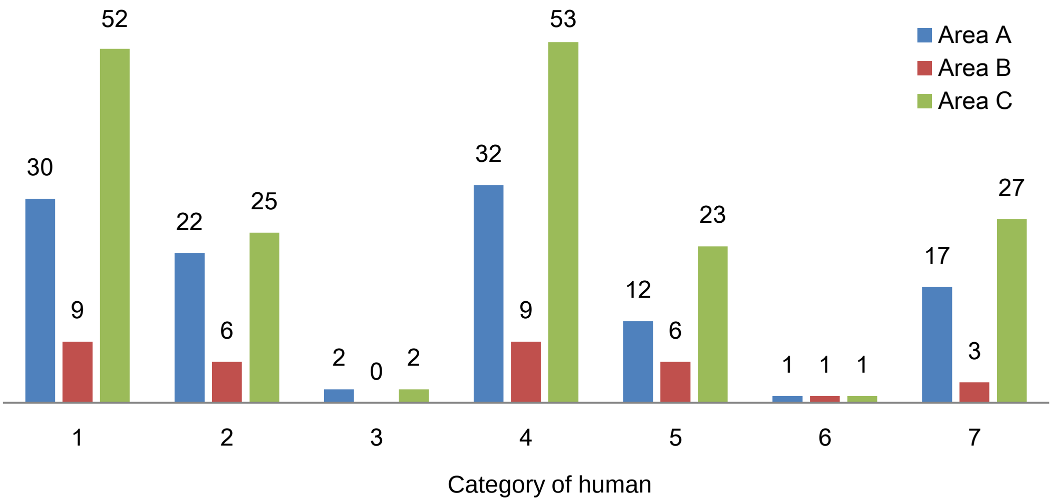


Fig. 4.2 Population in each Area **A**, **B** and **C**

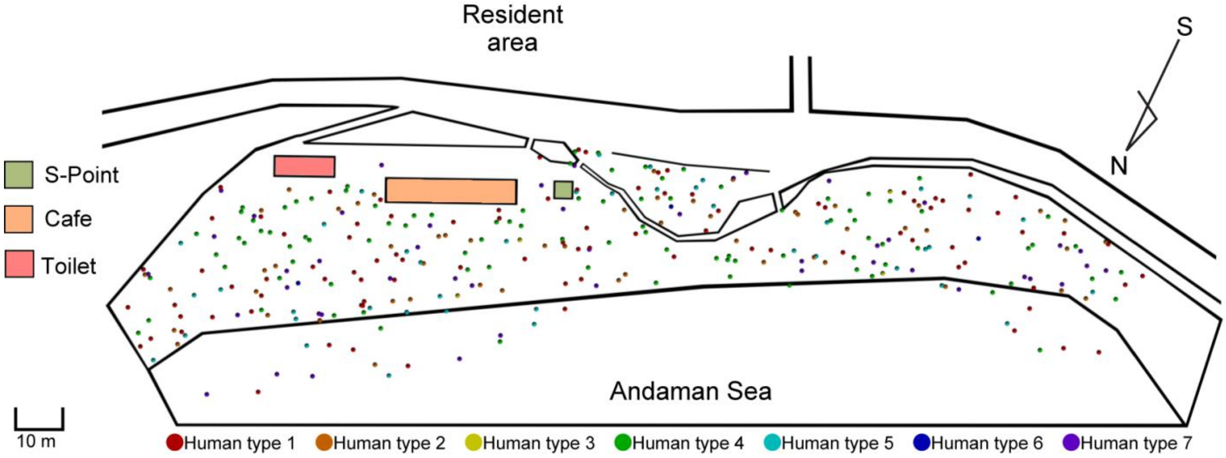


Fig. 4.3 Initial position arrangements of people for all case

4.4 Investigation of present condition of evacuation planning

For the initial condition of evacuation planning, the evacuation place is designated in the end of the main road leading from coast as shown in **Fig. 4.4**. This simulation is named as the sim-1. The people are instructed to evacuate toward the designated evacuation place. The graph of the time taken versus accumulative number of people who have completed the evacuation process is plotted as shown in **Fig. 4.5**. The time required to complete the evacuation process of the sim-1 is 312 seconds. The illustration snapshots of the sim-1 are shown in **Fig. 4.6**.

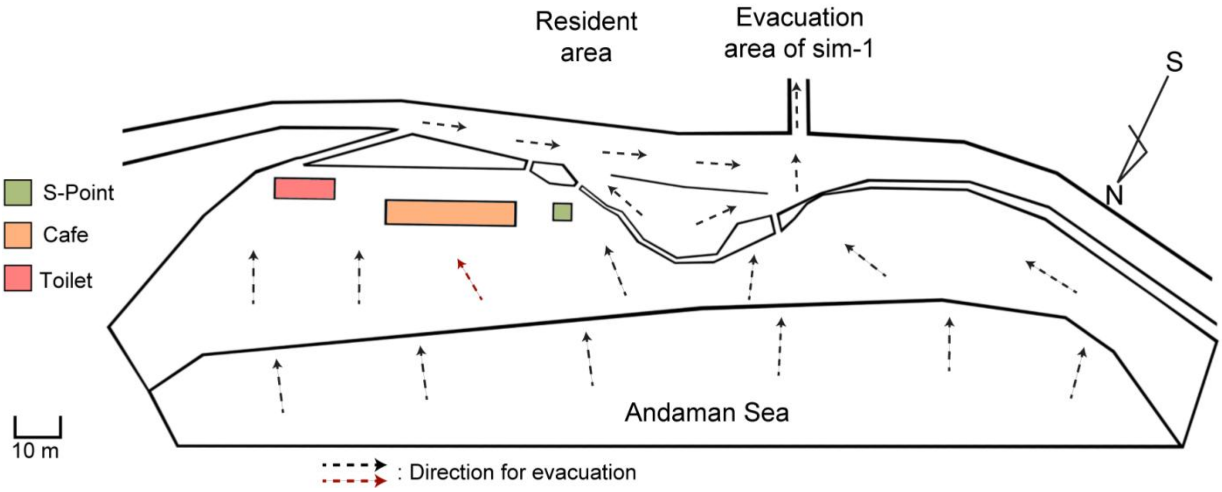


Fig. 4.4 Evacuation route and movement direction of people for the sim-1

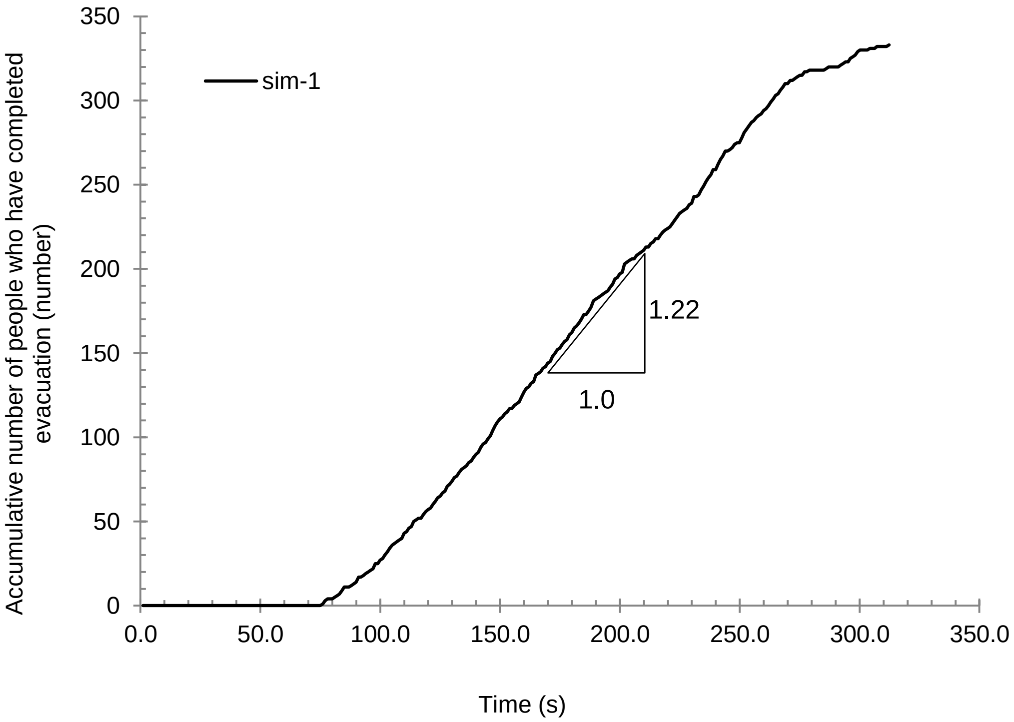


Fig. 4.5 Time series of the accumulative number of persons who complete evacuation process for the sim-1

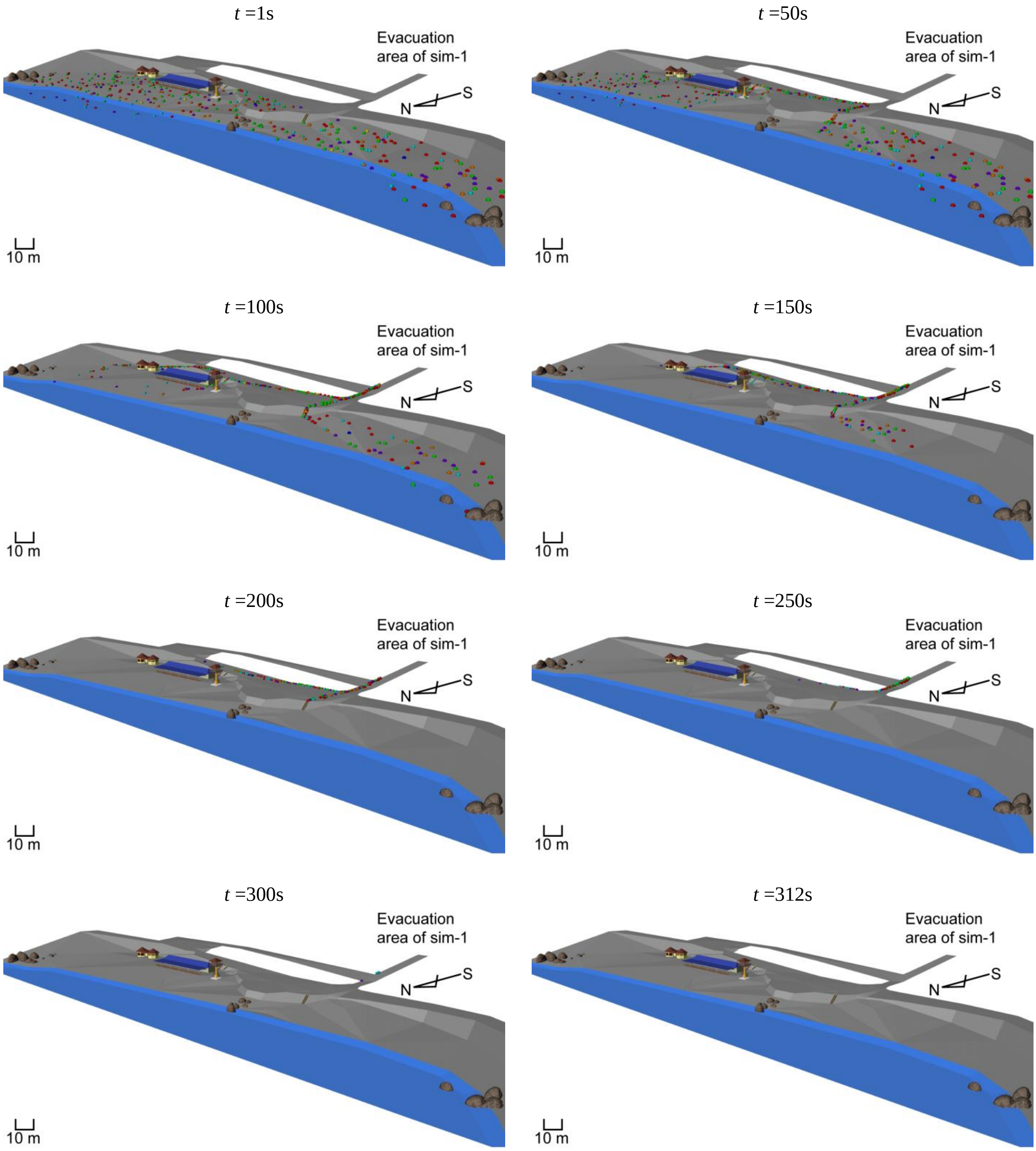


Fig. 4.6 The snapshots of the sim-1

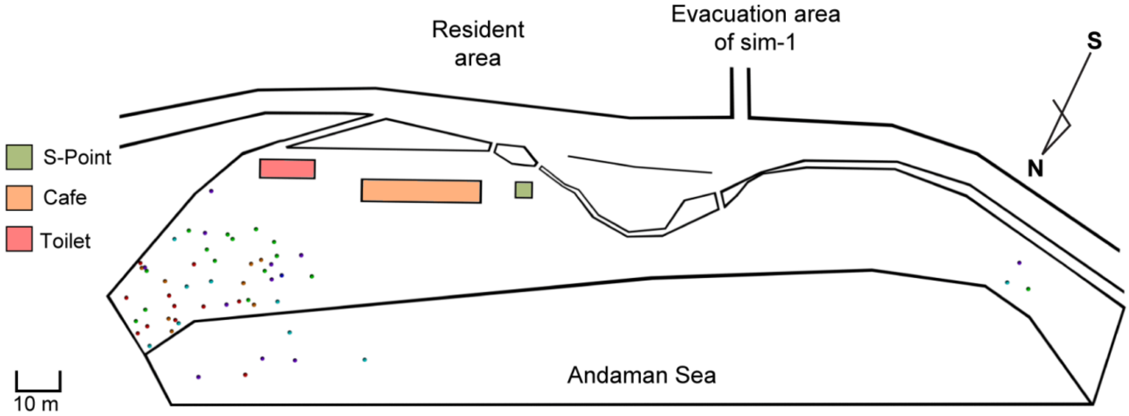


Fig. 4.7 Initial arrangement of persons who cannot complete evacuation process within 250 seconds in the sim-1

The assumptions were made by stating that all people need to complete the evacuation process less than 250 seconds. Therefore the deprivation area for quick evacuation has been disclosed. The distribution of initial positions of the people who cannot evacuate within 250 seconds is shown in **Fig. 4.7**. The number of the people who cannot evacuate within 250 seconds for the sim-1 is 55 persons. The interruption area for smooth evacuation was detected in the east end of the Area **C** and in the west end of the Area **A**. The significant factor of the delay in the evacuation process was the initial position of persons who are remote from the designated evacuation area. Thus, guideline regarding evacuation area should be investigated. The proposals toward the quick evacuation are shown in the following section.

4.5 Improvement of evacuation planning to the present condition

The late persons who are in the inconvenient area have been investigated in the alternative scenario. The alternative scenario is identified as the sim-2 for shortening the path between original location of people and the evacuation place, and in the same time, the completion time of evacuation is expected to be reduced. The evacuation route of the sim-2 is shown on **Fig. 4.8**. In the sim-2, persons arranged in the Area **C** are specified to evacuate to the new evacuation place, which is placed at the east end of the residential area. Whereas, the persons who in the Area **A** and **B**, evacuate to the same evacuation place as the sim-1. **Fig. 4.9** shows the accumulated number of people who have completed the evacuation for the sim-2. Meanwhile, **Fig. 4.10** shows the typical snapshots for the sim-2.

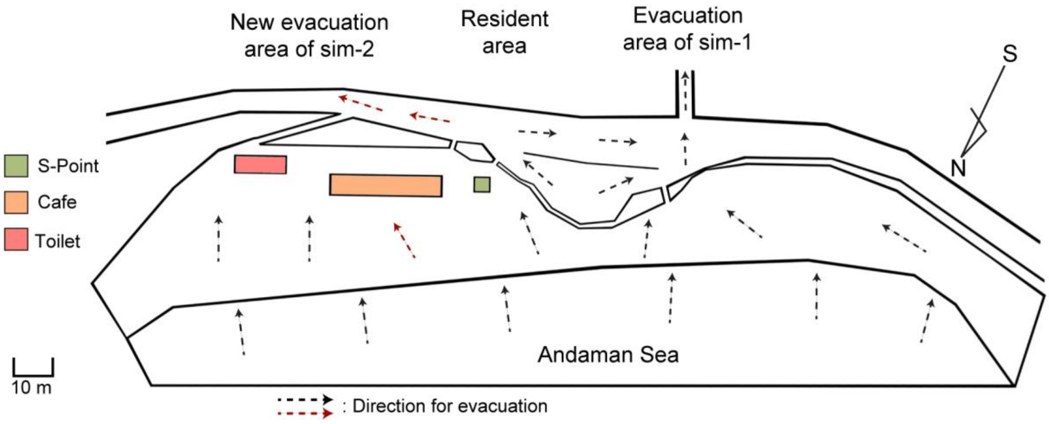


Fig. 4.8 Evacuation route and movement direction of people for the sim-2

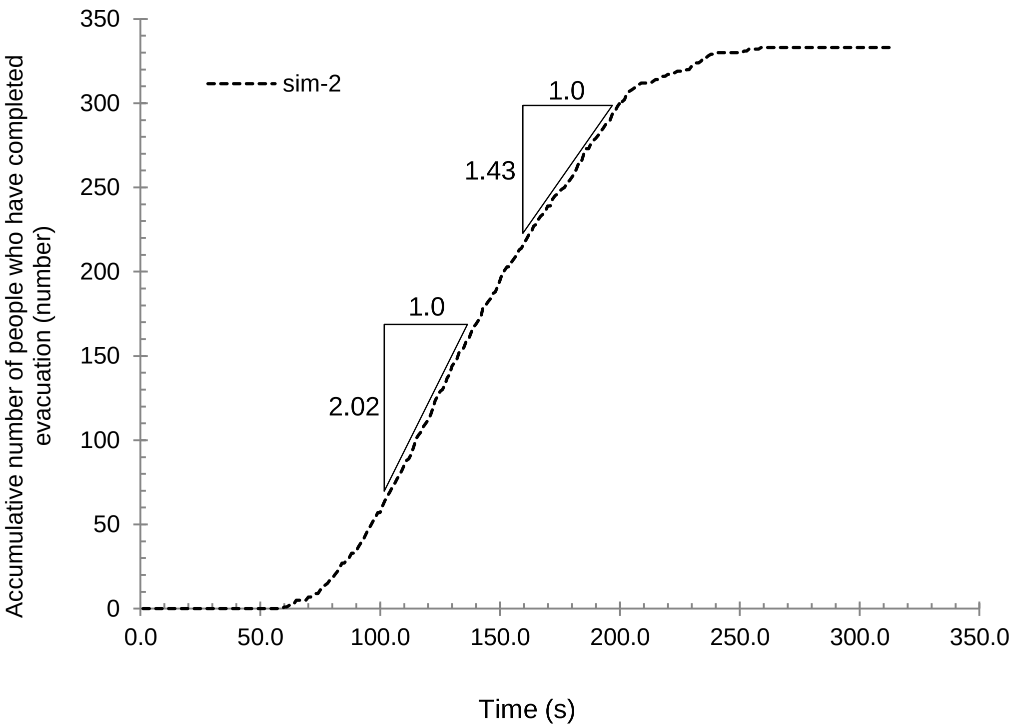


Fig. 4.9 Time series of the accumulative number of persons who complete evacuation process for the sim-2

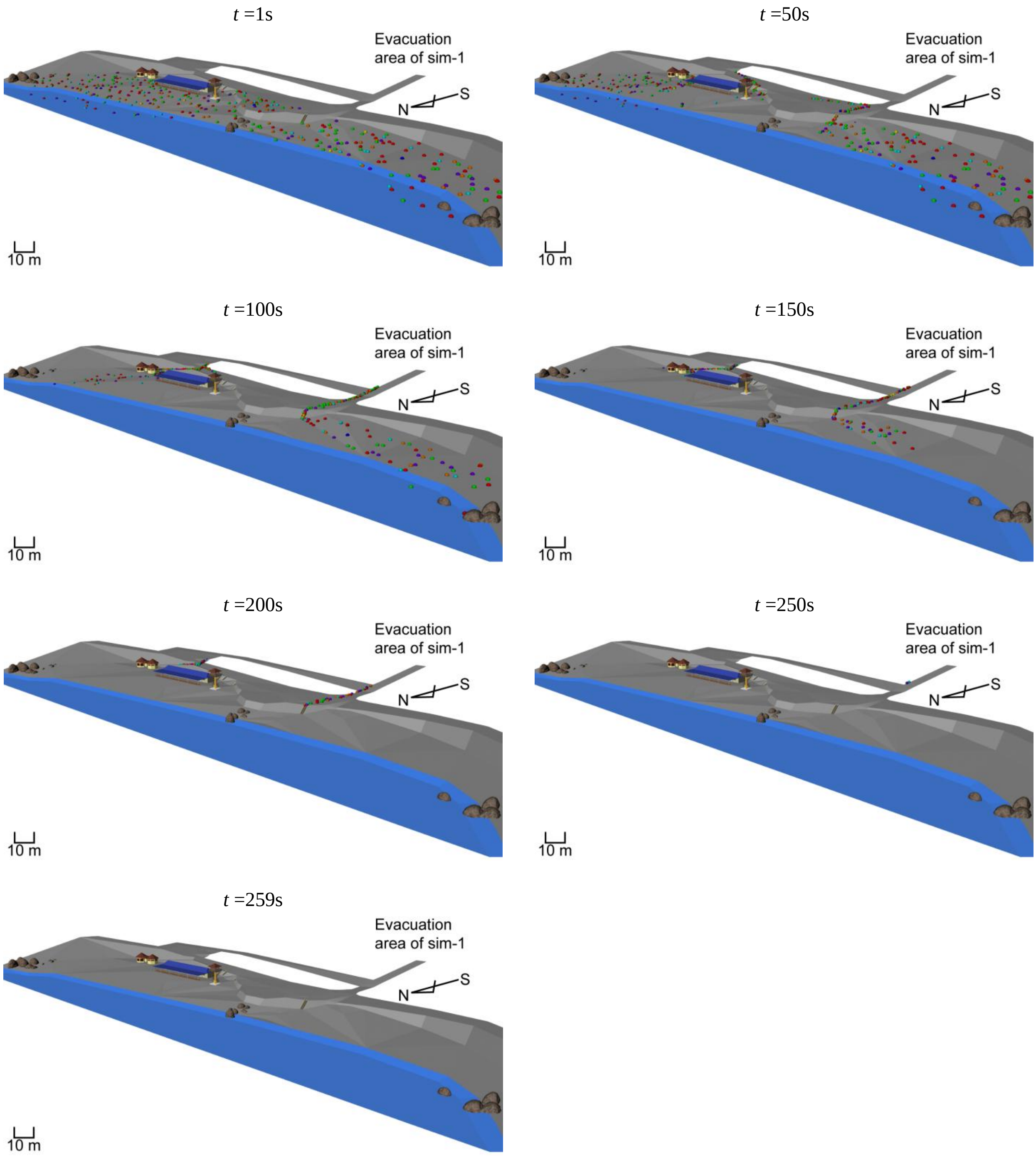


Fig. 4.10 Snapshot of the sim-2

On the other hand, the comparison between the sim-1 and the sim-2 gives the difference for effectiveness of the evacuation processes. The time series of the accumulative number of persons who have completed evacuation process for the sim-1 and the sim-2 are shown in **Fig. 4.11**. The efficiency for the evacuation of the sim-2 is found to be higher than that of the sim-1 with looking at the gradients of completion rate of evacuation. A decrease of 53 seconds is found in the sim-1 compared with the sim-2 from the viewpoint of the evacuation completion time. From these results, the additional evacuation place is effective to decrease the evacuation completion time.

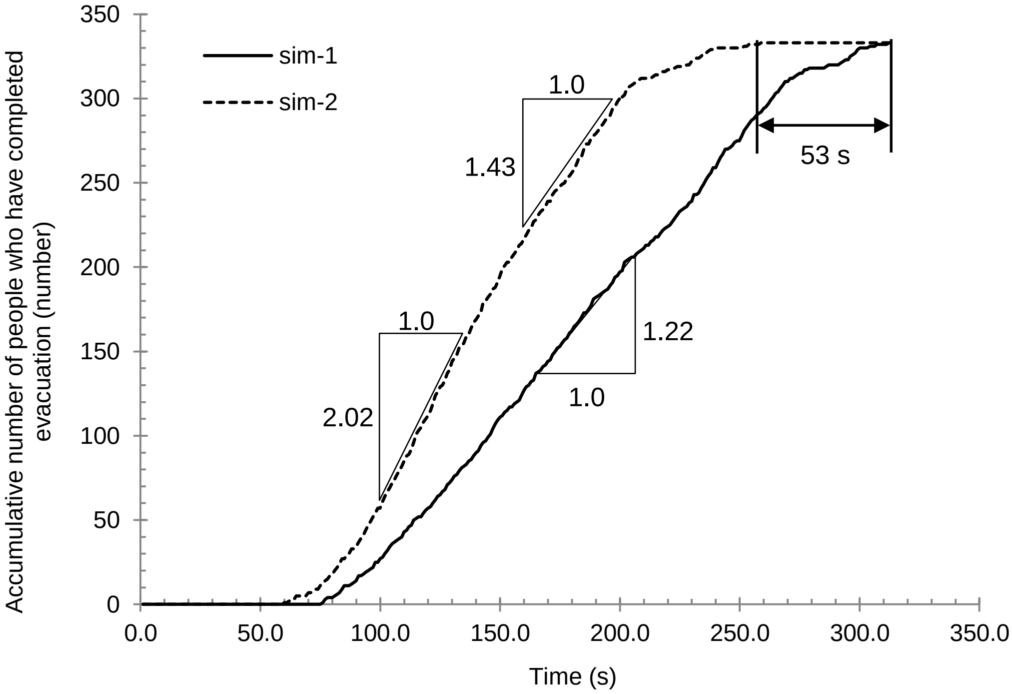


Fig. 4.11 Time series of the accumulative number of persons who complete evacuation process for the sim-1 and the sim-2

4.5.1 Assessment of initial position of visitor to the evacuation place

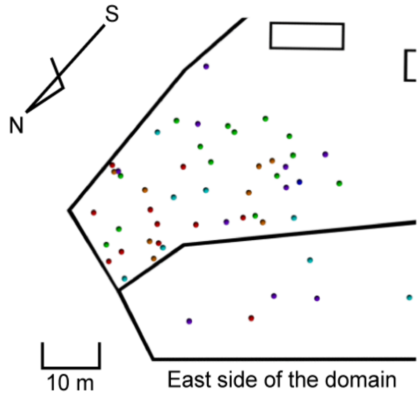
Three main factors that influence the evacuation process are as follows: (1) distance from initial position of person to the evacuation area; (2) type of human; and (3) surrounding area. As discussed previously, the initial position of the people who cannot evacuate within 250 seconds are as shown in **Fig. 4.7** without the composition of human type. In practice, the information of human type composition can be useful to develop an effective evacuation planning. Children and elders have slower average walking velocities in comparison to adults. Therefore, new evacuation area can be proposed to be built closer to the area that has higher percentage of elders and children composition to ensure quick evacuation process.

Fig 4.12 shows the distribution of persons according to the human type who failed to complete evacuation within 250 seconds around east side of the beach. The ratio (%) values stated in the table of this figure means the number of the people who failed to evacuate within 250 second divided by total number of people according to each human type (as presented in **Table 4.2)**. From **Fig. 4.12** the elder women (over 70 years old) gave the highest percentage with 33.3% who cannot evacuate within the time setting, followed by the children composition with 21.74%. These results proved that the evacuation area should be located near to the higher composition percentage of children and elder women.

Furthermore, **Fig. 4.13** shows the histogram of distance from the initial position to the designated evacuation place. As mentioned in the above statement (**section 4.3**), 55 persons are overdue. **Fig. 4.13** shows the distances to the evacuation place only for six different types of human selected randomly. The moving distance of each person for the duration of *n*-th computational time marching steps can be given by

$$L_n = \sum_{k=1}^{n} \left(\boldsymbol{u}_{hi} \cdot \boldsymbol{t} \right)_k \Delta t \tag{4.1}$$

in which, n = the time step, $\boldsymbol{t}$ = unit tangent vector along to moving direction. From the **Fig. 4.13**, the significant decrease to moving distance is shown dramatically. All total distance are reduced more than 60% and earlier completion of the evacuation is realized. In addition, the number of person who cannot evacuate within 250 seconds in the sim-2 is only 3 persons. The improvement by proposed the new additional evacuation area closest at Area **C** will be the reasonable choice.



Type of human	Gender	Age	Total number of people	People who fail	Ratio(%)
1	Male	10-39	93	11	11.82
2	Male	40-69	53	8	15.09
3	Male	over 70	4	0	0
4	Female	10-39	93	14	15.05
5	Female	40-69	41	8	19.51
6	Female	over 70	3	1	33.33
7	Child	5-9	46	10	21.74

Fig. 4.12 Distribution of persons according to the human type who failed complete the evacuation within 250 seconds for the sim-1

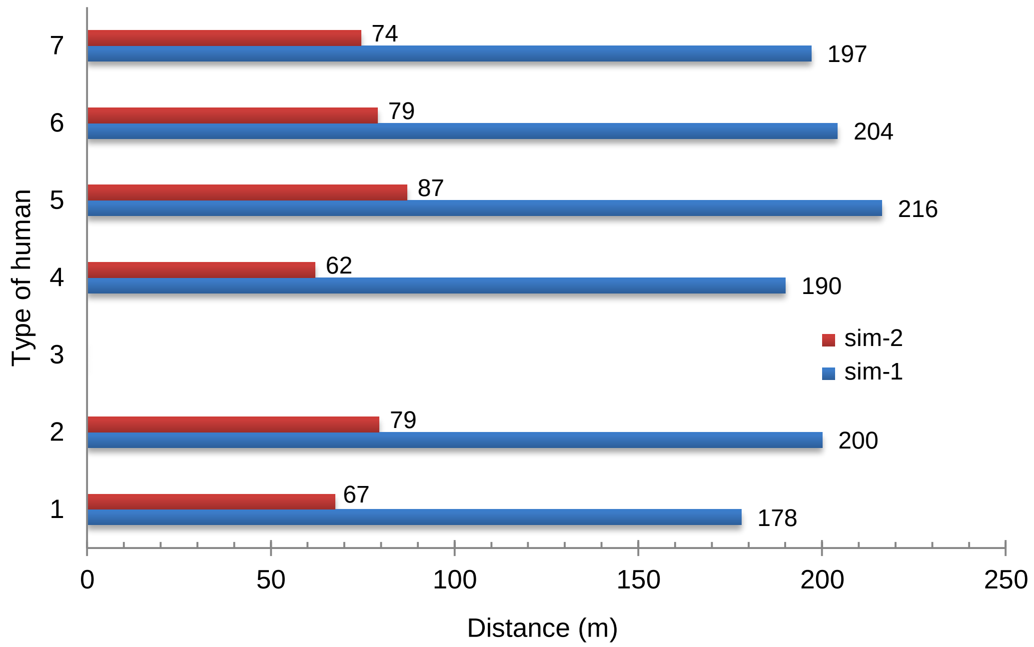


Fig. 4.13 Distance of initial position to the designated evacuation place for the sim-1 and the sim-2

4.5.2 Effects of the average local density and average walking velocity in the evacuation process

In this study, the average local density is referring to the average number of people in the perception domain. In practice, equilibrium walking velocity is influenced by the density of person in the perception domain. Therefore the value of average walking velocity fluctuation depends on local situation. If there are no congested trends, the flow of people will move smoothly toward designated evacuation area. **Fig. 4.14** and **Fig. 4.15** show the average walking velocity and average local density for the sim-1 and sim-2, respectively.

From the comparison between **Fig. 4.14** and **Fig. 4.15**, the similarity pattern of graph lines are clearly shown from the time t = 0 s to t = 70 s. This pattern is due to the reason that between that ranges of time, people move progressively. From the graphs related to the sim-1 (**Fig. 4.14**), the peak value of average local density occurs approximately at the time t = 220 s while such a drastic change cannot be confirmed in the average velocity. After the time t = 230 s, the value of average local density decrease significantly owing to the decrease of the persons under evacuation.

However, for the sim-2 (**Fig. 4.15**), the shape is totally difference from the sim-1 (**Fig. 4.14**). After the time t = 70 s, significant difference is found between sim-1 and sim-2. The highest value of average local density is recorded approximately at t = 110 s for the sim-2. This may be caused by the concentrated condition around the east side of the stairs. By referring to the **Fig. 4.8**, the moving direction in the Area C of the sim-2 is slightly different (as shown in red colored arrow) from that of the sim-1 (**Fig. 4.4**), and appointed moving direction gives closest distance to the evacuation area. Intensification of people moving in the direction toward the stairs near the toilet of the sim-2 leads the crowded condition on that area in early stage. However after the time t = 150 s, the local density value for the results of the sim-2 are gradually decrease because, at that time, more than the half of total number of people have been completed the evacuation process.

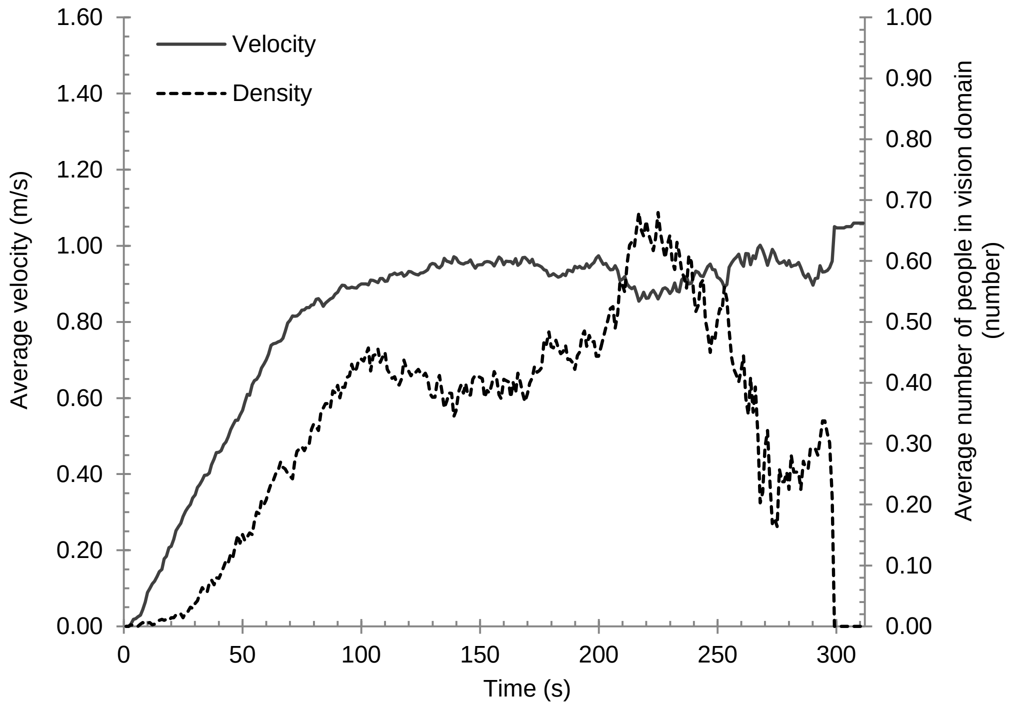


Fig. 4.14 Time series of average velocity and average number of people in vision domain for the sim-1

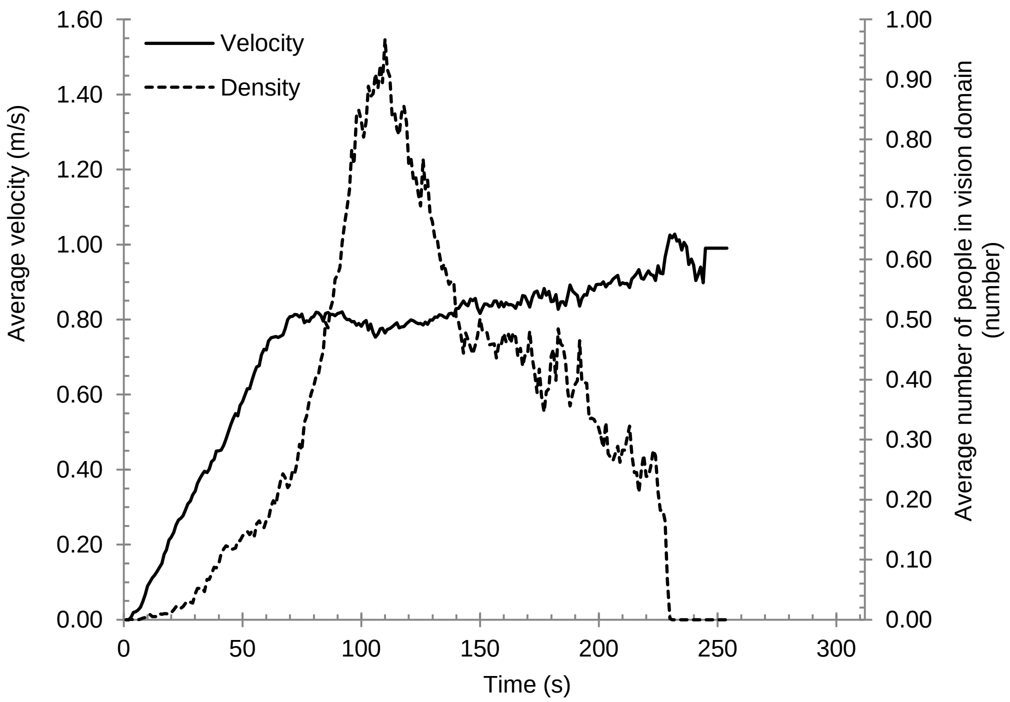


Fig. 4.15 Time series of average velocity and average number of people in vision domain for the sim-2

4.6 Computer graphic for the evacuation process at the Miami Beach

In this study, the process of the evacuation planning has been shown through the numerical simulation for the evacuation against tsunami at the Miami Beach, Penang, Malaysia by using the Crowd Behavior Simulator for Disaster Evacuation (CBS-DE) based on the Distinct Element Method (DEM). In the process of the evacuation planning, the inconvenient area has been revealed firstly, then the alternative planning for the improvement of the inconvenient area has been investigated, and the effect of the alternative planning has been shown quantitatively.

From the simulation results, the positions of each person have been tracked with detail information as discussed previously. Through the detail information obtained, a realistic virtual space by CG can be made. As shown in **Fig. 4.16**, the typical snapshots of evacuation process have been captured. This kind of the CG will be considered to be a useful tool for explaining the evacuation planning to the public, because CG movie has an advantage in the visual sense and people will be able to image evacuation process easily.

Fig. 4.16 Typical snapshot of CG movie for evacuation process at Miami Beach

In the near future, refinement of the simulator by introducing a group behavior (for example, family, couple and friend) will be performed. By introducing the group effect into the simulator, a little severe result for evacuation completion time can be obtained because the evacuation ability of person will be attenuated due to the action of waiting for the member of group or due to the action of something to help to group member.

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CHAPTER 5

NUMERICAL SIMULATION FOR EVACUATION PROCESS AGAINST TSUNAMI DISASTER AT TELUK BATIK BEACH IN MALAYSIA BY MULTI-AGENT DEM MODEL

5.1 Introduction

Regarding a tracking of individual motion, the two simulation models, namely CBS-DE model and CBS-DE with self-evasive action model, have contributed in investigating an evacuation planning. The self-evasive action model has been introduced into the existing CBS-DE model to simulate more realistic crowd behavior. With using this newly developed simulator, the pedestrian behavior, such as an avoidance of collision and an alignment between adjacent pedestrians are well reproduced in the contraflow. The contraflow may occur in the evacuation process due to an unexpected situation. Hence, in the present study, the self-evasive action model is validated firstly in comparison with an observation. Then the numerical simulation for the evacuation process including contraflow is performed at the Teluk Batik Beach in Malaysia. The effect of the self-evasive action model is shown in the context of the required time to complete evacuation.

5.2 Objective of the study

The CBS-DE and CBS-DE with self-evasive action models, like other available models, contain the mathematical equations and pedestrian ‘law’ to represent the movement behavior of assigned elements. And the simplifications of models are required to be confirmed their performance. In order to quantify the confidence in the accuracy of the models, the validation process is needed. Model validation is the primary process for quantifying and building credibility in numerical models. In the following section, performances of the CBS-DE model and CBS-DE with self-evasive action model are checked by simulating Malaysian walking behavior.

5.3 Validation of the models

5.3.1 Observation for collecting data

The observation of the movement of pedestrian was done through video shooting. The video footage was taken from pedestrian crosswalk in front of the KOMTAR building at Penang. The observation was conducted during peak time to obtain high density of pedestrian flow for two different directions (bidirectional). However, in this observation, the high density pedestrian contraflow was not successfully recorded. The number of pedestrians in one direction was quite larger than that in the other direction. Therefore the video-record was carefully selected to pick-up the moments where pedestrians walking in both directions have almost equivalent number.

Fig. 5.1 shows the dimension of observation area, the scale of which is 12.6 m in length and 4.6 m in width. From the videotape, the video format has been converted to the image format with the time interval of 0.5 seconds. Likewise the determinations of pedestrian trajectories have been extracted in every 0.5 seconds by the image analysis assisted by Human Behavior Simulator (HBS) plug-in for Autodesk® Maya® software. The procedure to obtain the pedestrian trajectories is nearly identical with the measurement of average walking velocity as discussed previously in Chapter 3. In this simulation, the equilibrium walking velocity of Malaysia citizen is employed and the pedestrian attribute is divided into seven categories estimated by subjective judgment.

In order to validate the CBS-DE with self-evasive action model, simulation results of the crossing behavior are compared with the observation. The comparisons of simulation results to the observation have conducted between the CBS-DE model and the CBS-DE with self-evasive action model. The moving patterns during the contraflow of pedestrian are closely observed. The CBS-DE model is prescribed as model-1 and the CBS-DE with self-evasive action model is prescribed as model-2. The two sets of cycles of pedestrian flow have been used to perform the validation.

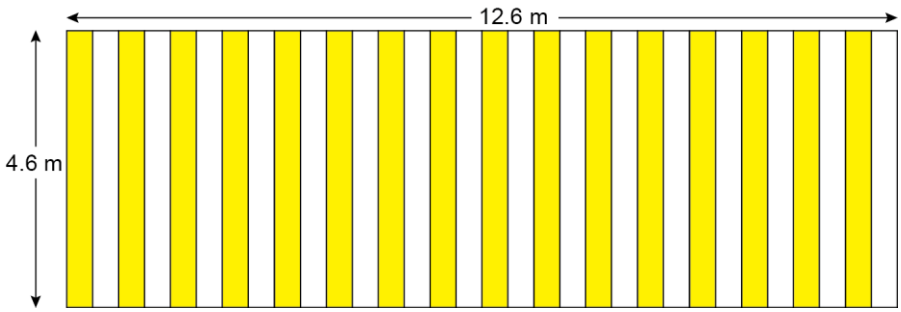

Fig. 5.1 Scale of pedestrian crosswalk

5.3.2 Effect of self-evasive action model

The validation results are diagrammatically shown in **Fig. 5.2** to **Fig. 5.5**. In **Figs. 5.2** and **5.3** the typical snapshots of pedestrian behavior of simulation results for model-1, model-2 and observation for each set are shown. The moving directions of black and white circles are designated in the negative and positive directions, respectively. From **Fig. 5.2**, at the time t = 8.5 s, the distinction of pedestrian moving patterns could not be found significantly between model-1 and model-2. Moving pattern of the model-1 and the model-2 are almost similar and have slight difference from observation. However, at the time t = 11.5 s, the differences are clearly shown. The alignment without including congestion shown in the observation is reproduced in the model-2. While such alignment is not formed in the result of the model-1, resultantly the congestion occurs. Thus the effect of the self-evasive action model was confirmed.

Meanwhile, as for **Fig. 5.3**, the significant difference is not found in the position of the pedestrian between the model-1 and the model-2. While, the position of the pedestrian shown in the model-1 and the model-2 are differ from the observation result. This will cause the remarkable difference of the results between simulation and observation at the time t = 11.0 s. However, the effect of the introducing of the self-evasive action model to enhance the performance of the pedestrian model is confirmed in comparison to the results between model-1 and model-2. Specifically, although the congestion occur in the model-1, on the other hand, such kind of congestion is not seen in the model-2 as the observation result shows.

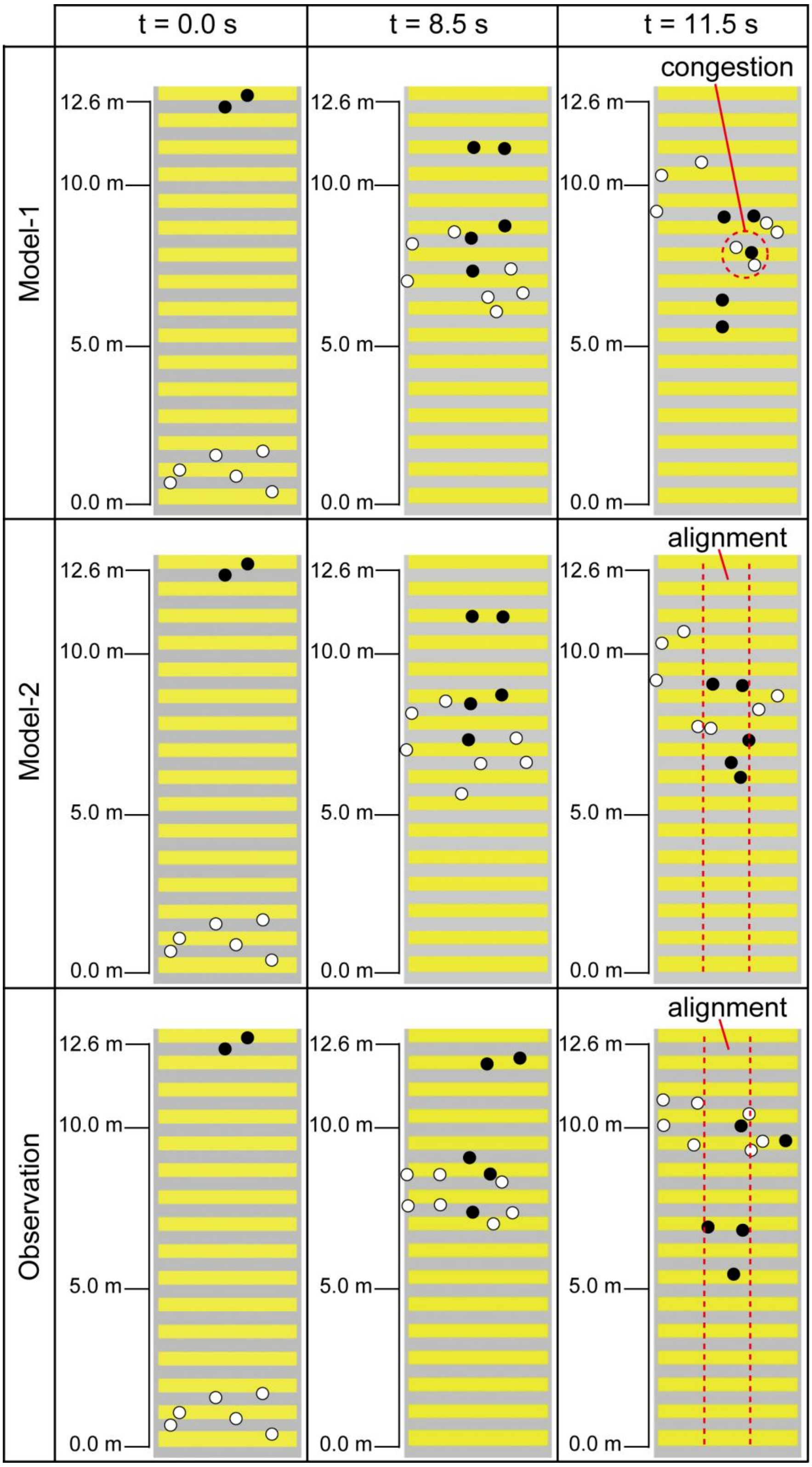

Fig. 5.2 The snapshot of contraflow of model-1, model-2 and observation for the validation process set 1

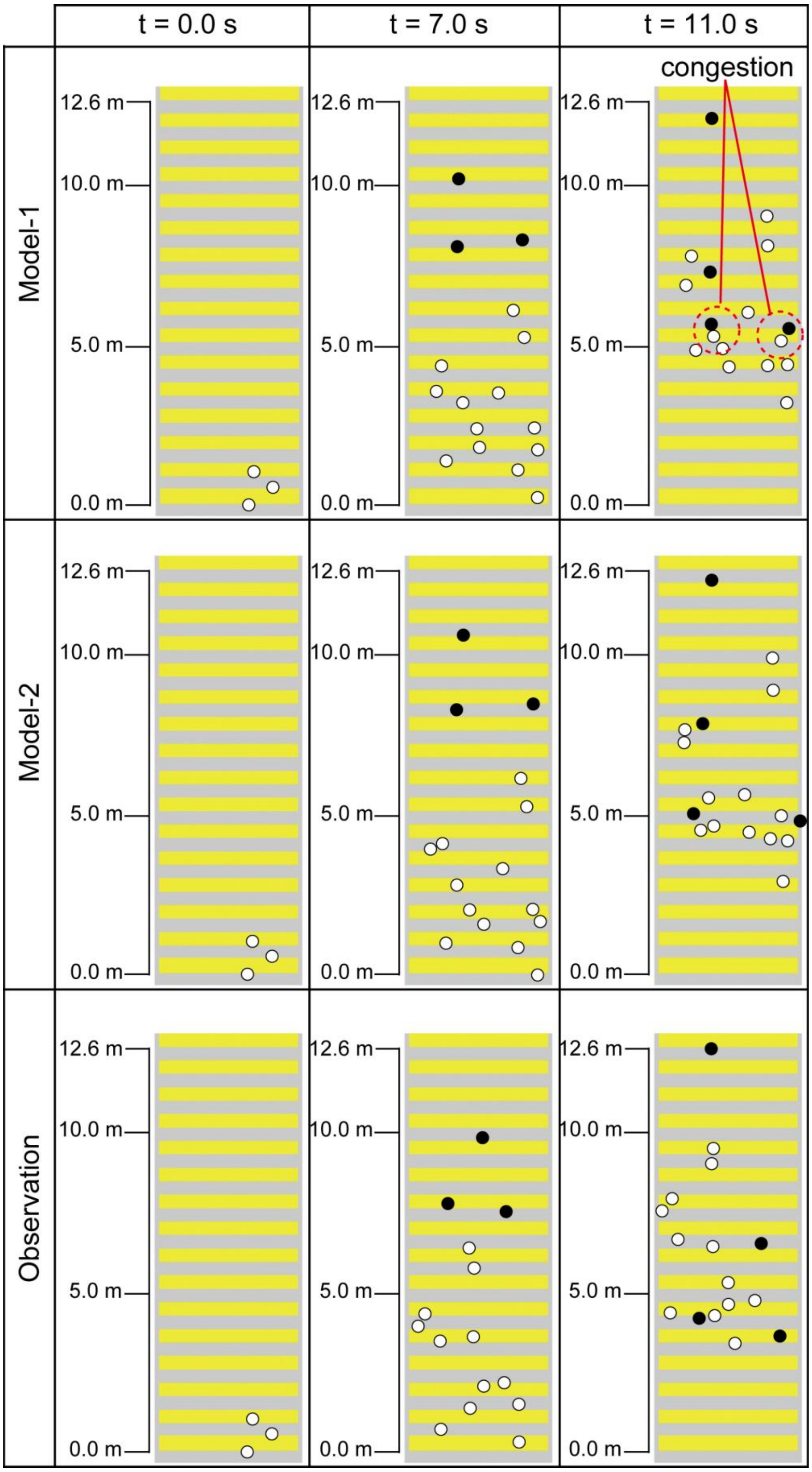

Fig. 5.3 The snapshot of contraflow of model-1, model-2 and observation for the validation process set 2

To confirm the effect of the self-evasive action model, the domain of the self-evasive action model and the moving direction are overlaid in **Figs. 5.2** and **5.3**. In addition the domain of the self-evasive action model is also added on the observation results. **Figs. 5.4** and **5.5** which are related to the **Figs. 5.2** and **5.3**, respectively, show the moving direction and the self-evasive action domain of each pedestrian who moves in the negative direction. Regarding **Fig. 5.4**, the moving direction at the time t = 8.5 s, between model-1 and model-2 is considerably different. The anticipatory behavior is shown in the result of the model-2. Likewise, same behavior is confirmed from observation results. On the other hand, such tendency is not found in the result of the model-1.

From the **Fig. 5.5**, the anticipatory behavior can be seen from the results of the model-2 and observation. Meanwhile, the congestion occurs in the results of the model-1 because of the lack of the anticipatory behavior by the self-evasive action model.

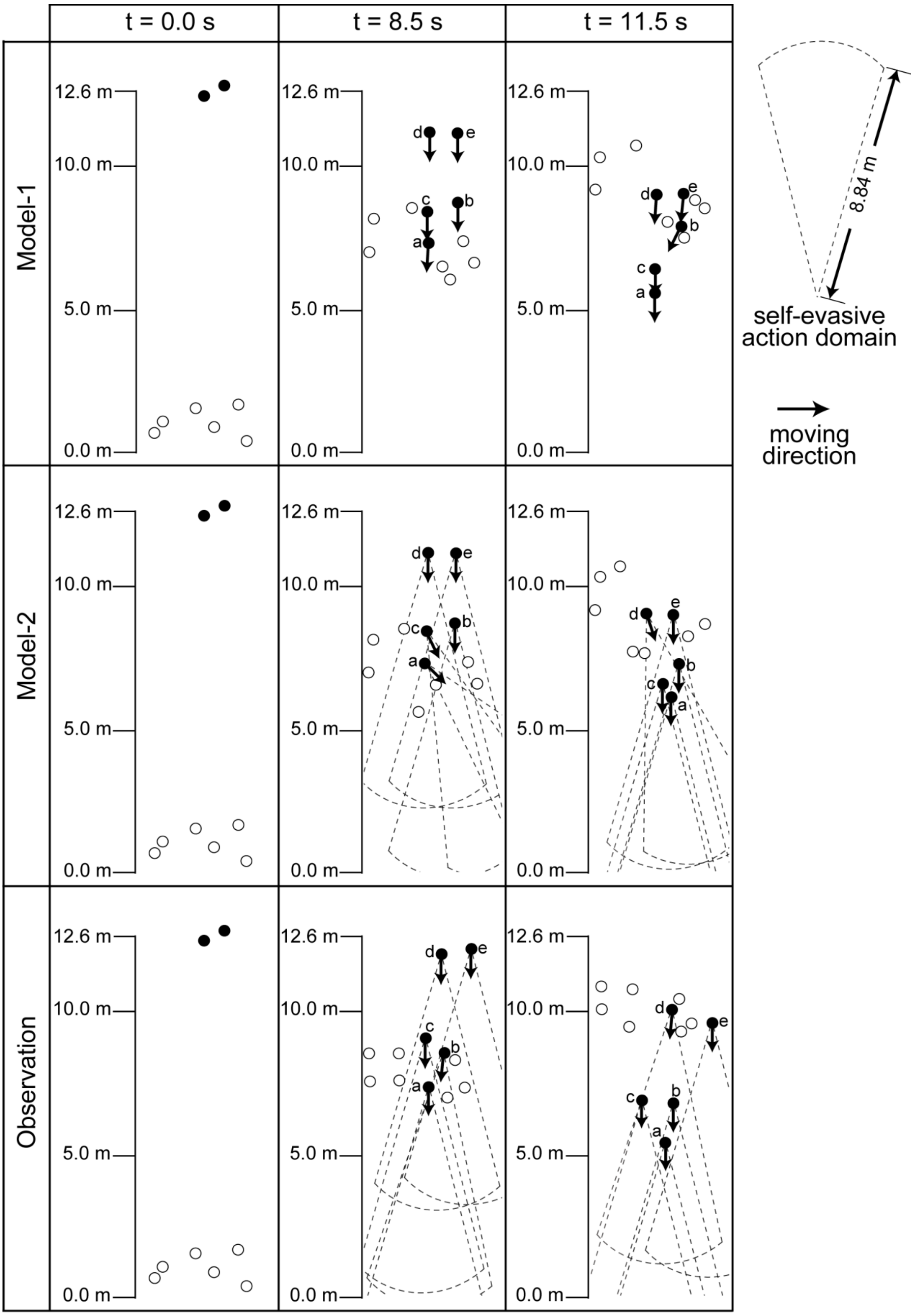

Fig. 5.4 The self-evasive domain and movement direction for each pedestrian who move in the negative direction for the validation process set 1

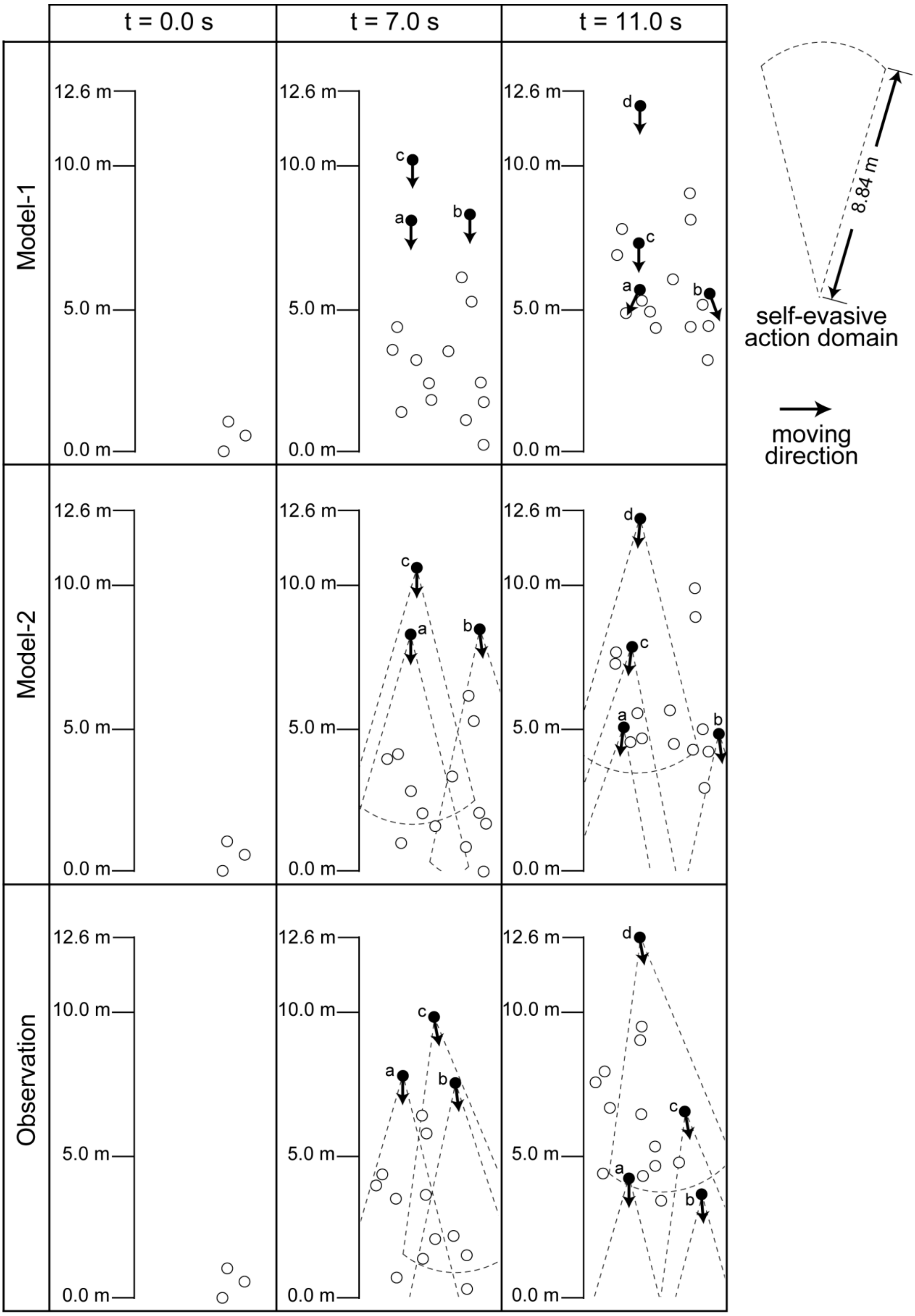

Fig. 5.5 The self-evasive domain and movement direction for each pedestrian who move in the negative direction for the validation process set 2

The time series of the average walking velocity of pedestrians who move in the negative directions for both sets (validation process set-1 and set-2) of the model-1, the model-2 and the observation are shown in **Figs. 5.6** and **5.7**. In **Fig. 5.6**, around the time t = 12.0 s, the decrease of the average velocity is shown in the model-1, and this decrease is due to the occurrence of the congestion as shown previously in **Fig. 5.2**. Likewise, in **Fig. 5.7**, occasional decrease of average velocity is found around the time t = 10.0 s in the result of the model-1. However, generally good agreement between observation and simulation of the model-2 is shown in the both **Figs. 5.6** and **5.7**.

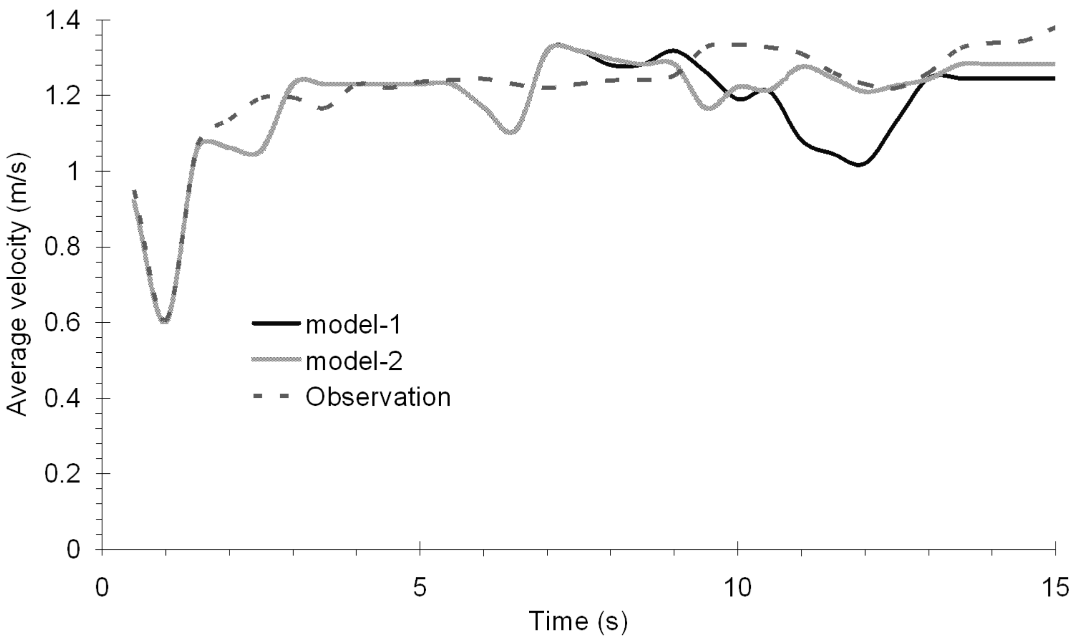

Fig. 5.6 Time series of the magnitude of average walking velocity of pedestrian who move in the negative direction for the validation process set 1

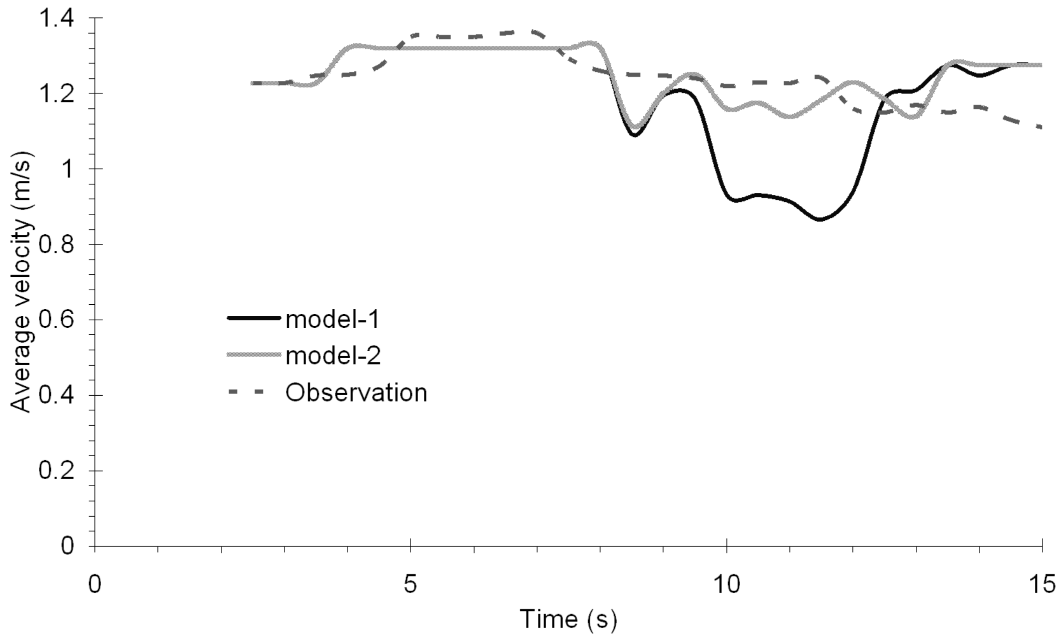

Fig. 5.7 Time series of the magnitude of average walking velocity of pedestrian who move in the negative direction for the validation process set 2

Furthermore, **Figs. 5.8** and **5.9** show the time series of averaged angle variation and these figures correspond to validation process set 1 and 2, respectively. In these figures, the pedestrians who changed the walking direction to the left are shown by positive value, and vice versa. As reflected in the figures (see **Figs. 5.8** and **5.9**), the pedestrian in the model-2 began to change their moving directions earlier than the pedestrian in the model-1. The delay in change of moving direction contributes high probability to the occurrence of the collision with pedestrians moving from opposite directions. Thus, the effect of the self-evasive action model was revealed. And the validity of the value of the radius using in the domain of the self-evasive action model might also be shown.

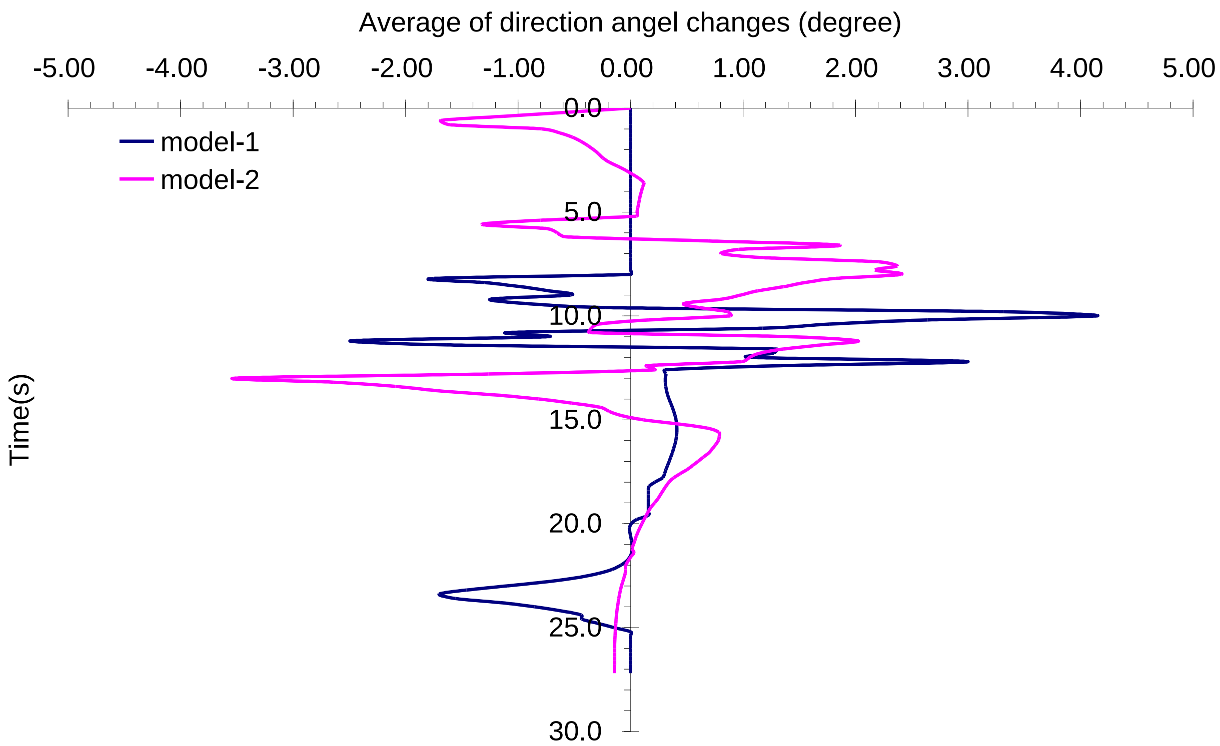

Fig 5.8 The time series of the average of direction angel change for the validation process set 1

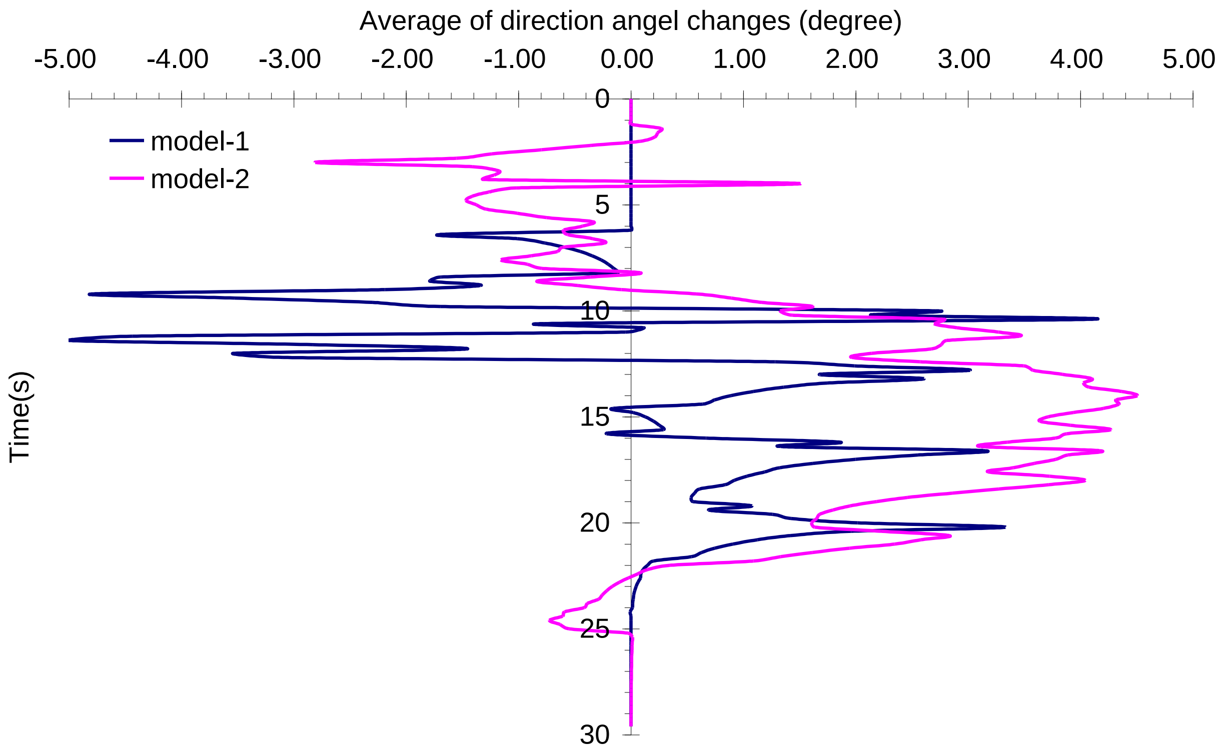

Fig 5.9 The time series of the average of direction angel change for the validation process set 2

5.4 Evacuation process

The Teluk Batik Beach is a place which received thousands of visitors. It located at the west coast of the state of Perak in Peninsular Malaysia. The topography of the Teluk Batik beach is sloping and surrounded by hills covered with tropical rain forest. The sloping beaches make it an attraction for the visitors from local and international. Furthermore the crowded condition may happen especially during public holidays and weekends. **Photo 5.1** shows the view of the Teluk Batik Beach. The Teluk Batik Beach is the resort space. Hence a suitable planning, which assures safety of people during emergency or disaster is required, even when an unusual behavior of the crowd occurs.

Photo 5.1 View of Teluk Batik Beach

5.4.1 Simulation setup

According to the field surveys, the culminant distribution of population is observed as shown in **Table 5.1**. A total of 1,512 people during the peak time are shown. And the area is an attractive place to relax with family and friends. Visitors at the age range of 10 to 39 years old of male and female were recorded in the highest percentages of which are 32.01% and 33.00%, respectively. On the other hand, for the range of age over than 70 years old for both genders is unrecorded.

The population is classified into seven categories by gender and age groups, and equilibrium walking velocities are used based on derived value from distribution of average walking velocity of Malaysian pedestrian. Besides, **Fig 5.10** shown the initial arrangement of the people in the coast area which is arrange randomly.

Table 5.1 Detail population in Teluk Batik Beach

Category	Sex	Age	People	Ratio	Velocity
1	Male	10-39	484	32.01	**1.38**
2	Male	40-69	161	10.65	**1.14**
3	Male	>70	0	0.00	**0.99**
4	Female	10-39	499	33.00	**1.20**
5	Female	40-69	194	12.83	**1.04**
6	Female	>70	0	0.00	**0.89**
7	Child	5-9	174	11.51	**1.06**
		Total	**1512**	**100 %**	

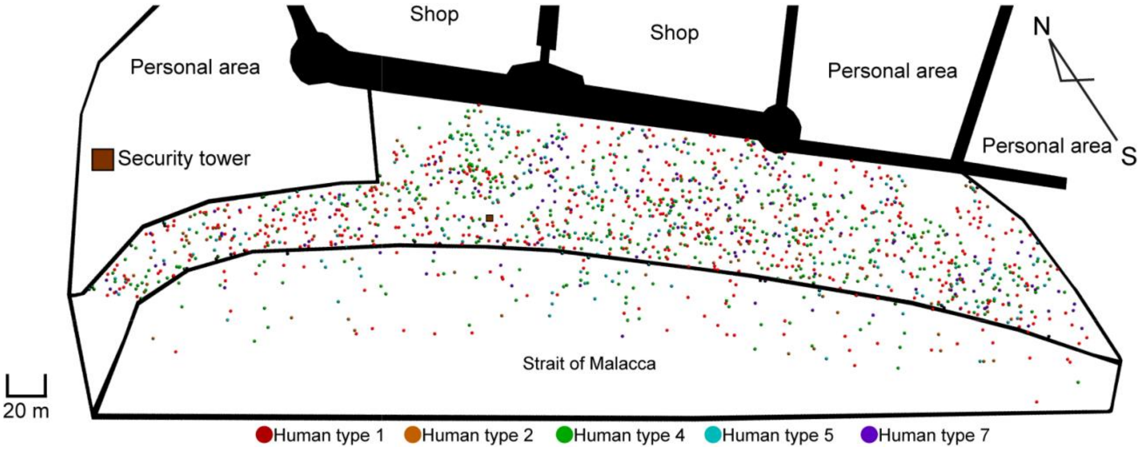

Fig. 5.10 Initial position arrangements of people at the Teluk Batik beach

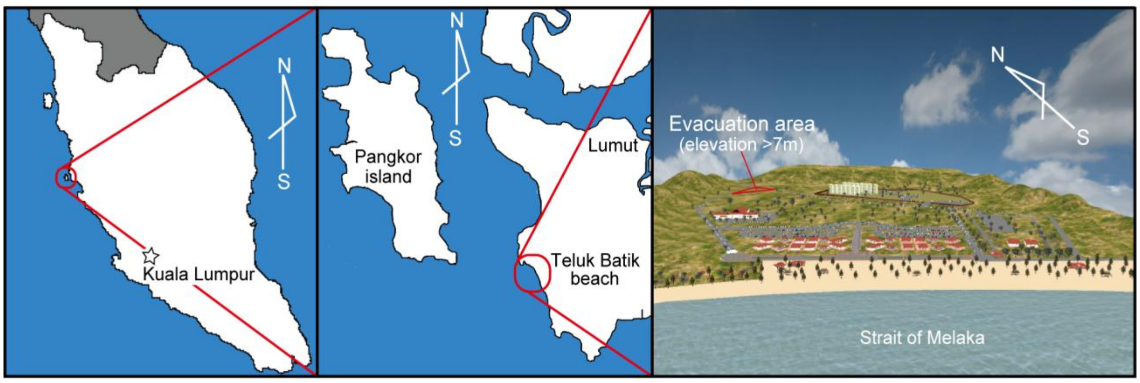

Fig. 5.11 Perspective view of Teluk Batik Beach

Fig. 5.11 shows the computational domain around the Teluk Batik beach. The beach area is surrounded by the beauty of the lush tropical rain forest. The length of shoreline is approximately 620 m and the width is about 75 m. The setup of evacuation route for the simulation of evacuation process against tsunami is shown in **Fig 5.12**. The completion of evacuation is assumed that all people move safely to the designated evacuation place.

In emergency situations, human movement will be irregular and such behavior will not be out of control. And the stampede will occur and the contraflow will be formed. Therefore in this study, a situation having a contraflow of people is assumed. The assumption made as follows. The people in the area **A** typically use the road 1 as a convenient road to access from parking area to the beach area. However, the road 1 has a problem and the road 1 cannot be used for the evacuation. In contrast, the people in the area **B** use the road 2 as the usual access road from parking area to the beach area. At the time of evacuation process, the people in the area **B** does not notice that the road 1 is closed until they arrive at check point, so after arriving at the check point, they return back to the road 2 to continue the evacuation. Besides, the assumption that information about tsunami warning spreads at the security tower with the speed of 1.5 m/s is given. And the people are to start their movement after receiving the tsunami warning.

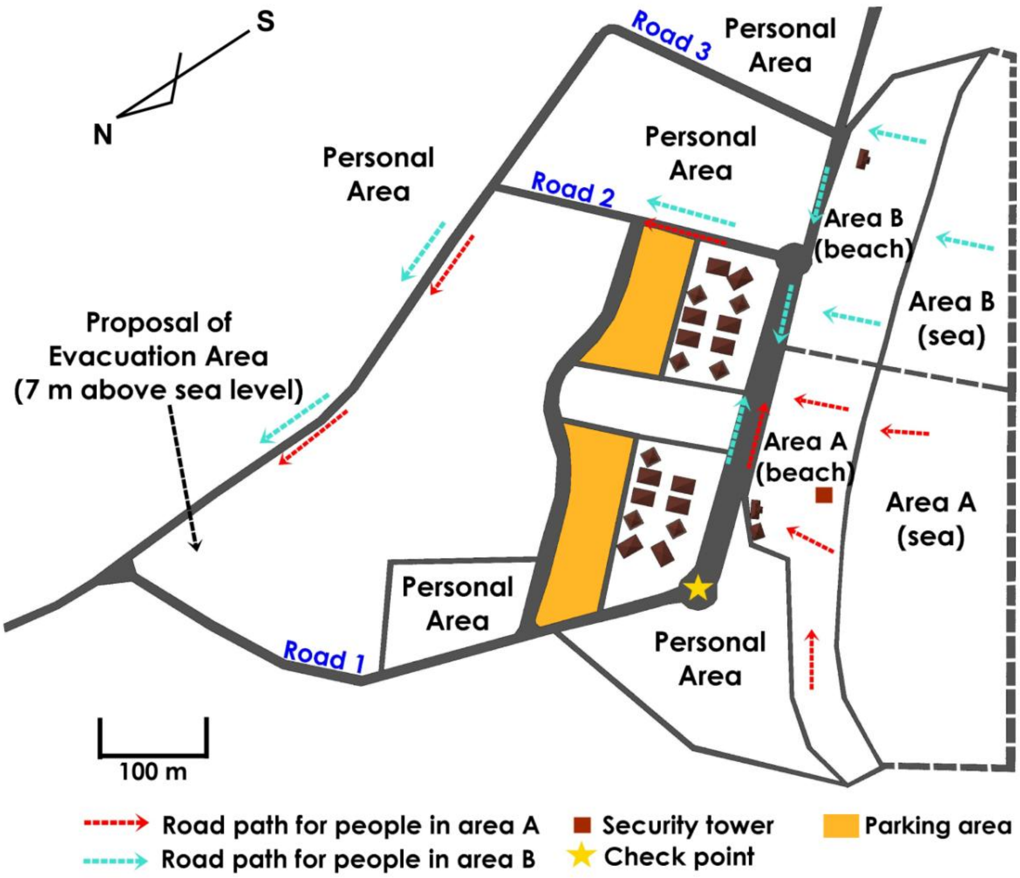

Fig. 5.12 Evacuation route

5.4.2 Effect of self-evasive model

To demonstrate the effect of self-evasive action, the two-test areas to record the information have been installed as illustrated in **Fig. 5.13**. First test area is set in the area where the contraflow will be shown and the second test area is set in the area where the unidirectional flow will be shown. The detailed information of average velocity and the average number of pedestrian in the perception domain are recorded to analyze the distinction between the CBS-DE model and the CBS-DE with self-evasive action model. As mentioned above in the **section 5.2**, the CBS-DE model and the CBS-DE with self-evasive action model are prescribed as the model-1 and the model-2 respectively.

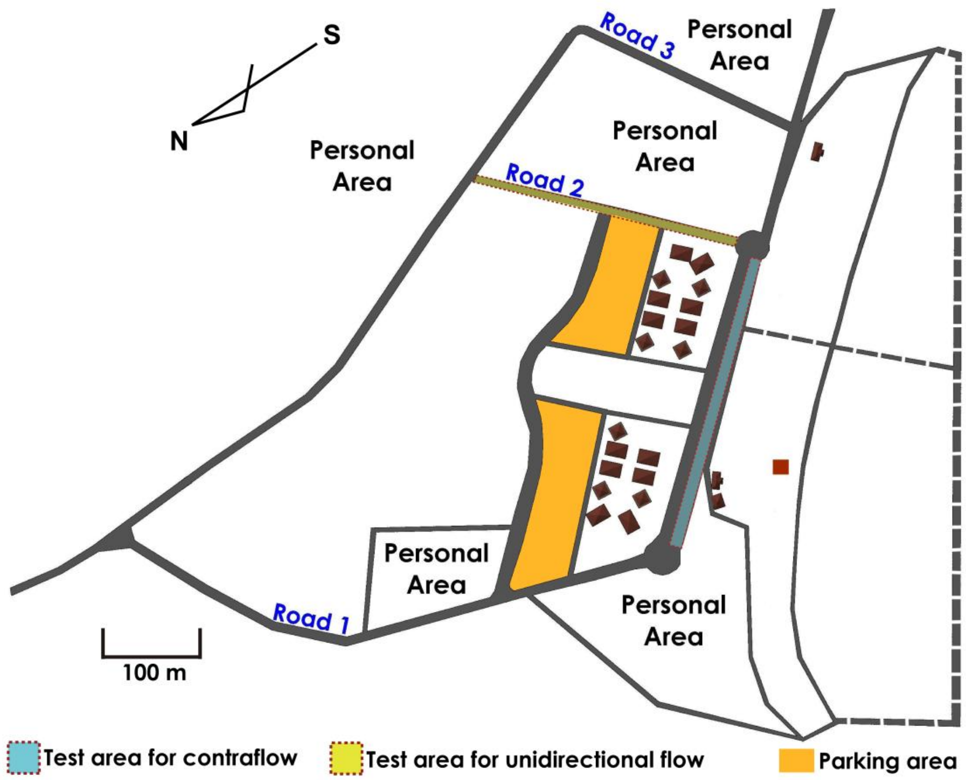

Fig. 5.13 The location of the test area to obtain detailed information

5.4.2.1 Test area for contraflow

Figs. 5.14 and **5.15** show the average walking velocity and average local density versus time for the model-1 and the model-2, respectively, at the test area for contraflow. Significant differences can be found by comparison between two models.

Fig. 5.14 shows that, in the model-1, the average local density increases dramatically at the beginning of evacuation process from the time t = 100 s. The highest value of average local density is recorded around t = 195 s, with the value 2.07 people/m^2. After the time t = 200 s the value of local density decreases with fluctuations till the time t = 600 s. The inverse correlation between the average walking velocity and the average local density is shown. In addition the congested condition will be occurred from the time t = 100 s to the time t = 600 s in comparison with the result of the model-2 (see **Fig. 5.15**).

On the other hand, referring to the model-2 shown in **Fig. 5.13**, the time series related to both velocity and density are more stable than those of the model-1. The highest value of average local density is occurred at the time t = 146 s with the value is 0.64 people/m^2. And this is obviously lower than that of the model-1. Furthermore the velocity remains constant with about 1.0 m/s. From these results, the smooth evacuation process can be found in the model-2 in comparison to the model-1.

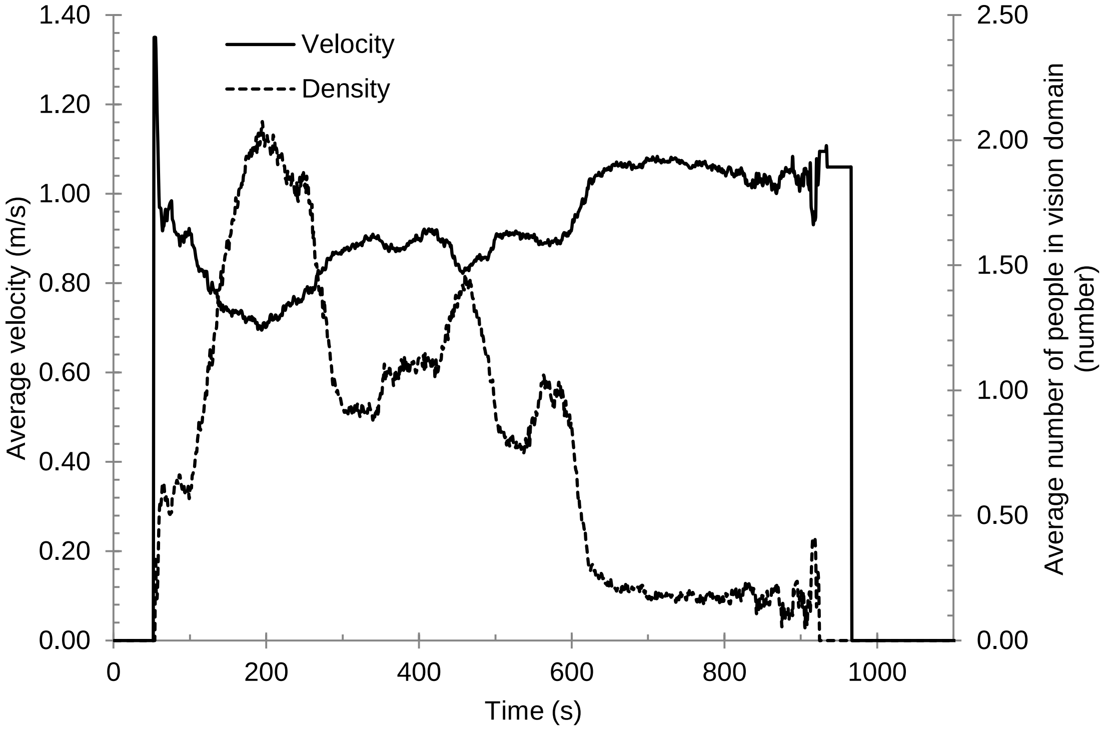

Fig. 5.14 Time series of average velocity and average number of people in vision domain for model-1 at test area of contraflow

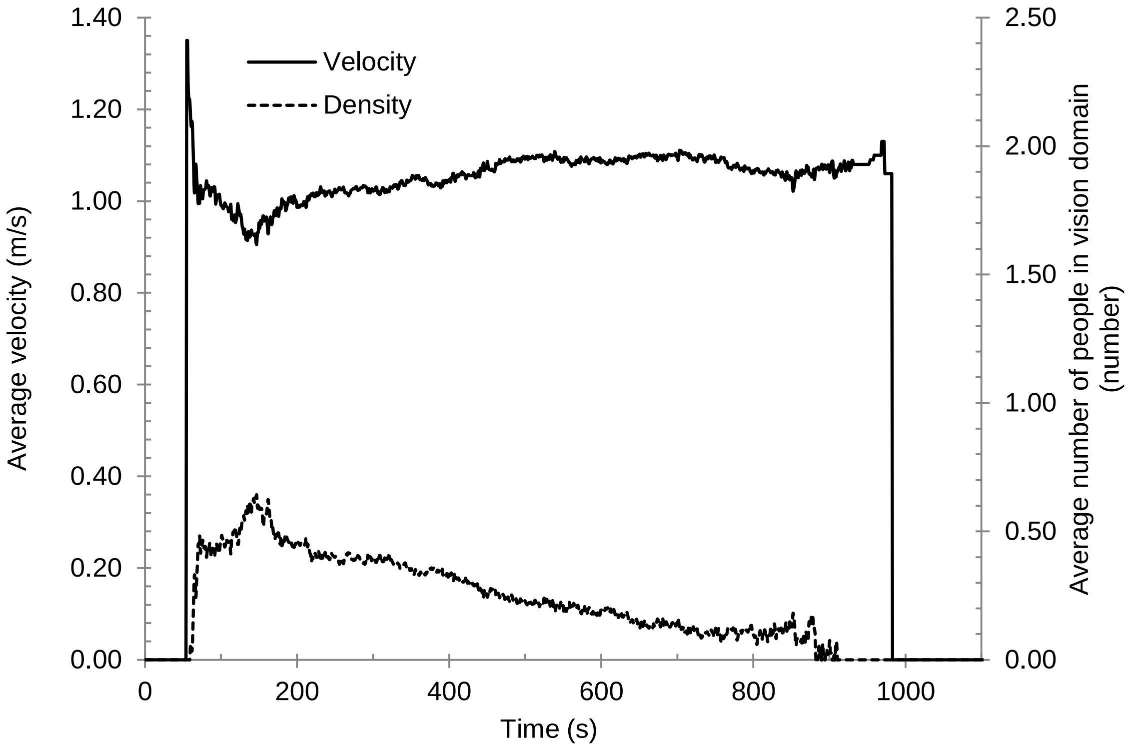

Fig. 5.15 Time series of average velocity and average number of people in vision domain for model-2 at test area of contraflow

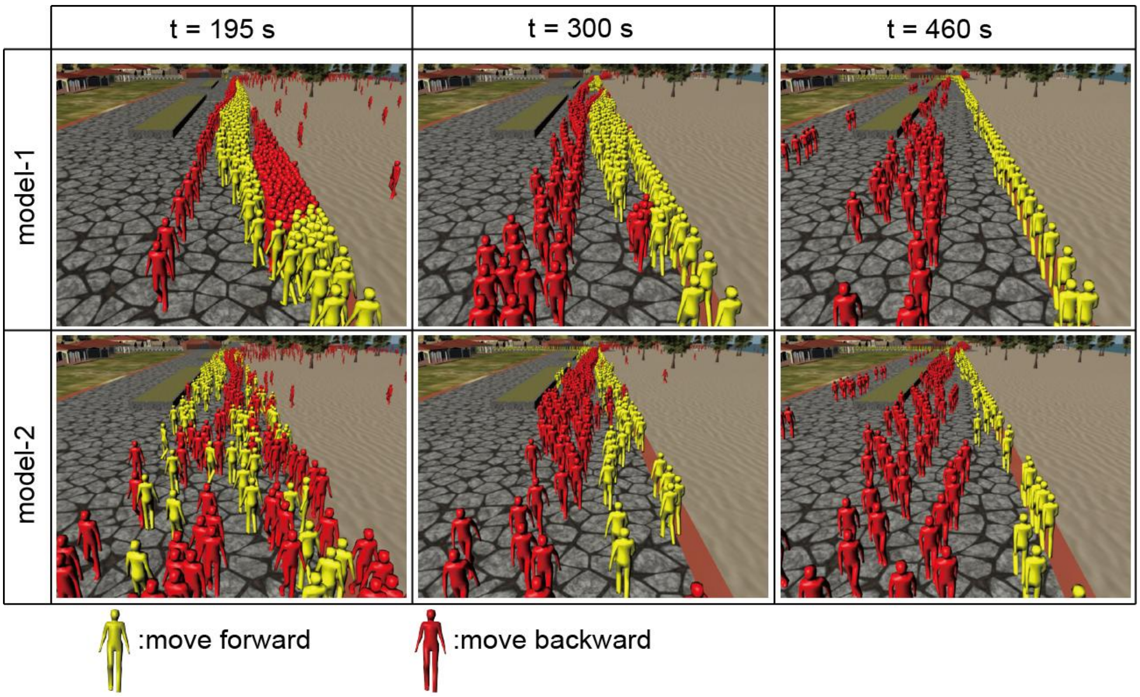

Fig. 5.16 The snapshot of CG in test area of contraflow for model-1(up) and model-2(down)

In order to show the differences between the model-1 and the model-2 visually, the CG snapshot has been taken at the location showing contraflow. **Fig. 5.16** shows the typical snapshots for evacuation process at the test area for contraflow. The significant congestion with crowd can be found in the snapshot of the model-1 at the time t = 195 s. And this kind of congested condition is often observed as shown in the snapshots of the model-1 at the time t = 300 s. The congestion with crowd is obviously considered as unnatural event. On the other hand, such severe congestion is not found in the model-2. The people tend to follow the front people rather than making their own paths to evacuate. Such action would be contributed to the formation of the alignment. The smooth contraflow would be simulated in the model-2.

5.4.2.2 Test area for unidirectional flow

Figs. 5.17 and **5.18** show the time series of both average velocity and average local density for the model-1 and the model-2, respectively, in the test area for the unidirectional flow. The highest value of average local density for the both models is recorded less than 0.5 people/m^2. Referring to **Figs. 5.17** and **5.18**, the average of the local density values was significantly lower in comparison to that of the test area for the contraflow. And the obvious differences between model-1 and model-2 cannot be found in the test area for the unidirectional flow. This fact shows that the self-evasive action model plays significant role in the contraflow condition.

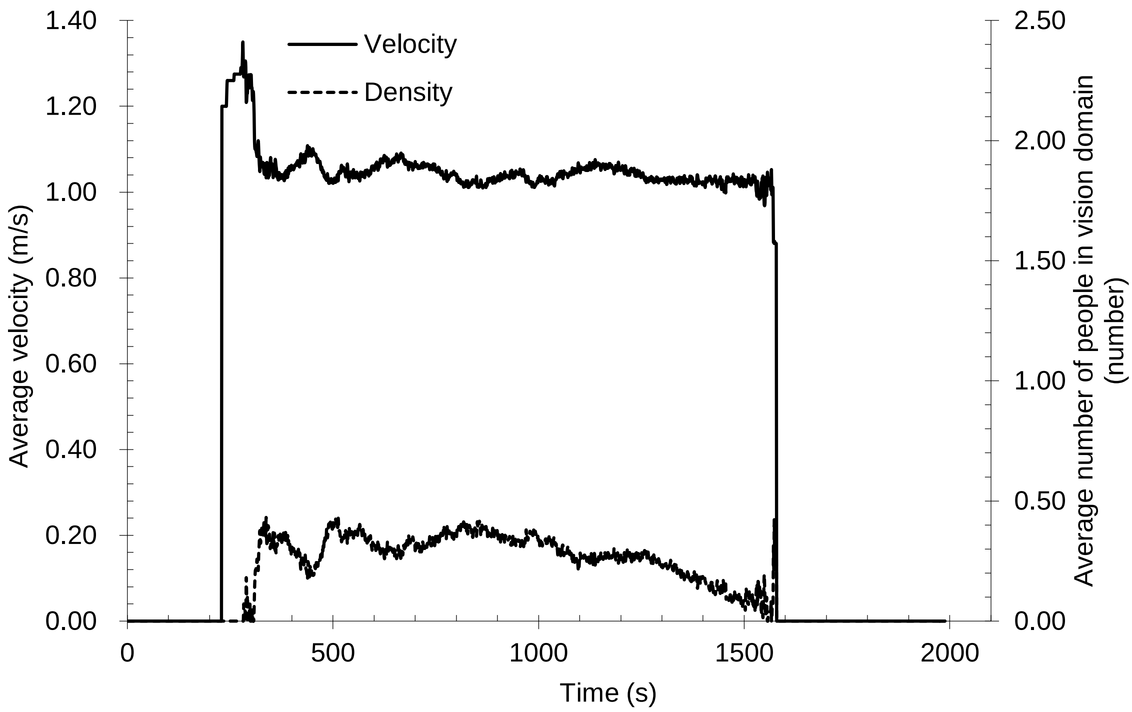

Fig. 5.17 Time series of average velocity and average number of people in vision domain for model-1 at test area for unidirectional flow

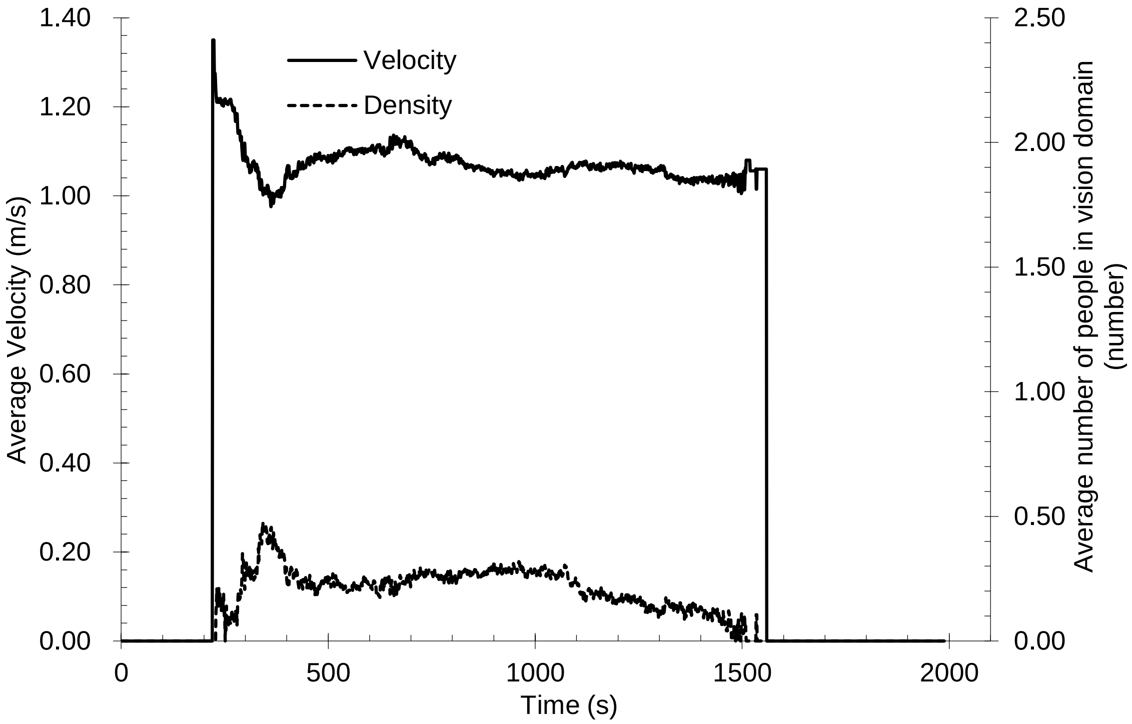

Fig. 5.18 Time series of average velocity and average number of people in vision domain for model-2 at test area for unidirectional flow

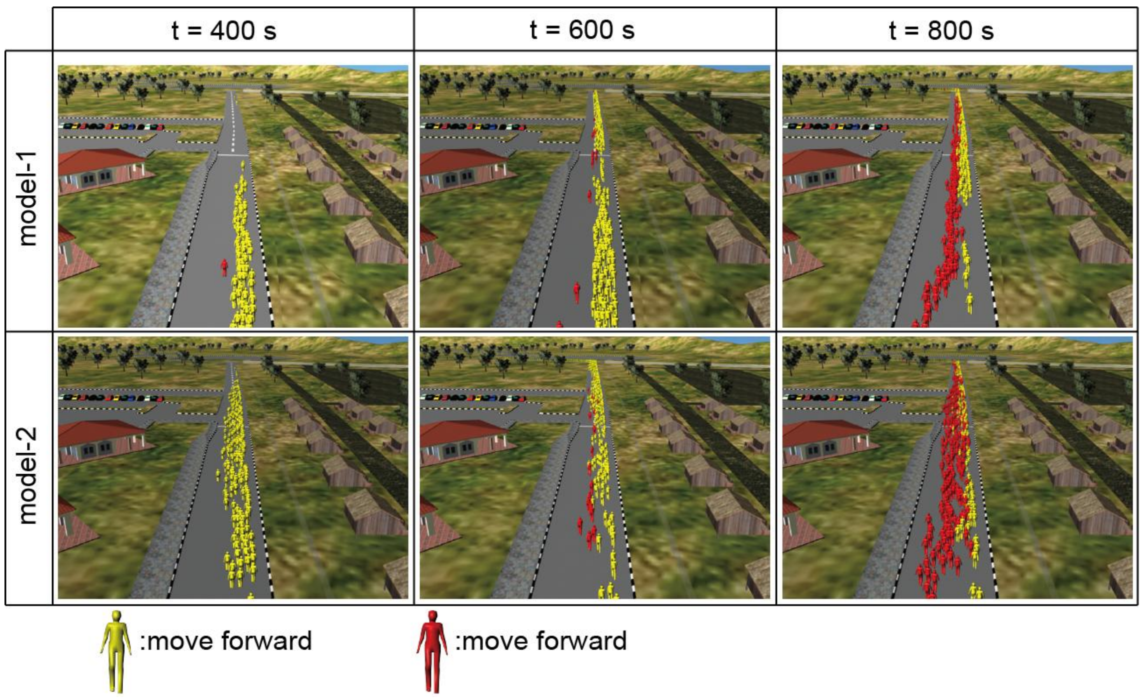

Fig. 5.19 The snapshot of CG in test area of unidirectional flow for model-1(up) and model-2(down)

Fig. 5.19 shows the typical snapshots for evacuation process in the test area for unidirectional flow. From the snapshots at the time t = 400 s, the evacuation process of people in the model-2 appears faster than the model-1. Referring to the snapshots, the slight difference of arrangement is found. The behavior of simulated people in the model-2 is scattered whereas in the model-1, the behavior of simulated people is rather organized with forming a line. The slight scattering in the evacuation process simulated in the model-2 would be caused by the introduction of the self-evasive action.

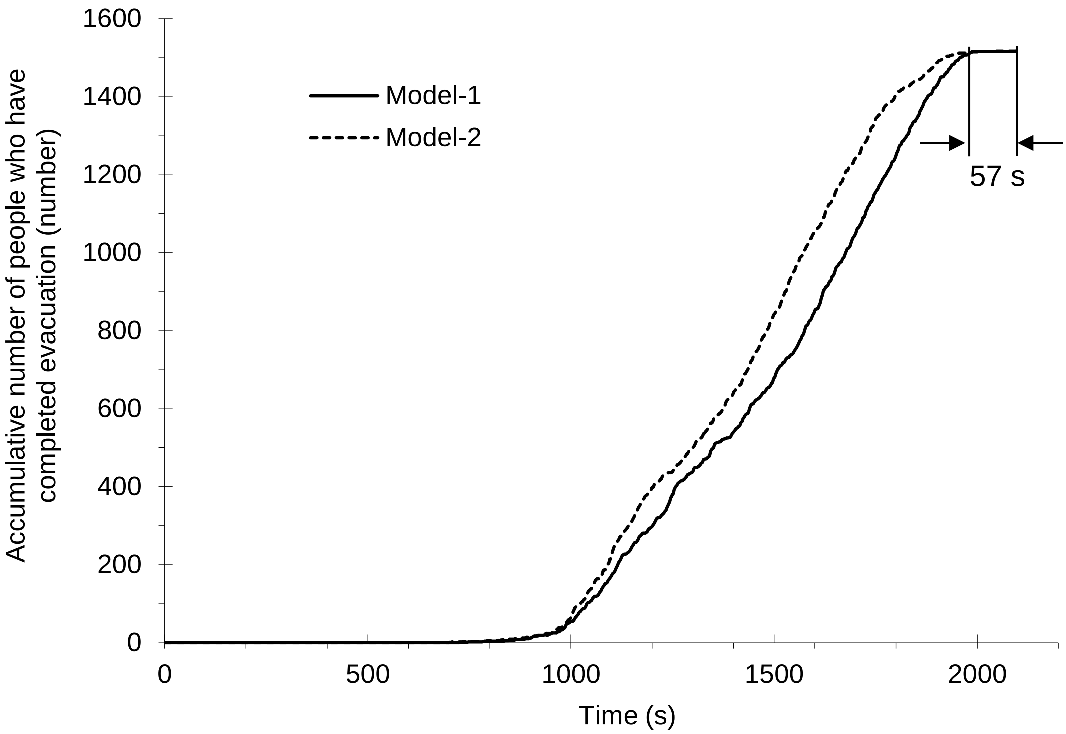

Fig. 5.20 Time series of the accumulative number of persons who complete evacuation process for model-1 and model-2

5.4.3 Completion time for evacuation

Fig. 5.20 shows the time series of the accumulative number of people who have completed evacuation. The completion time of evacuation in the model-2 is decreases by 57 seconds in comparison to that of the model-1 as shown in **Fig. 5.20**. This fact will support the effect of self-evasive action model. Significance of the development of appropriate crowd behavior model to the implementation of this kind of evacuation simulation is inferred.

5.5 Conclusion

The explanations of the comparison between the two models are mentioned qualitatively and quantitatively. At the beginning, the validity of the CBS-DE with self-evasive action model has been shown by comparison with observed results of the contraflow at the crossing. From the simulated results, the congested situation was occurred in the model-1 (model using the CBS-DE without self-evasive) while did not occurred in the model-2 (model using the CBS-DE with self-evasive). Result from the model-2 was nearly identical to the observation of pedestrian behavior.

The evacuation process against tsunami disaster at the Teluk Batik beach in Malaysia has been performed by using the CBS-DE with and without the self-evasive action model. The significant effect of the introduction of the self-evasive action model has been found in the simulation results. From the simulation results of contraflow using in the model-2, the reproducibility of pedestrian behavior is more realistic because the unnatural congestion situation is not generated.

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CHAPTER 6

CONCLUSIONS

6.1 Preamble

This chapter summarizes the main findings of this research with regards to numerical simulation of evacuation process due to tsunami for different hypothetical scenarios which was conducted primarily at Malaysia. At the early chapter, four objectives had been designed in conducting this research; begin with establishing data of the average walking velocity and pedestrian behavior for Malaysian citizen. Thereafter, from the data obtained and numerical simulation by CBS-DE model, the effectiveness and the efficiency of the evacuation process during tsunami disasters are investigated. Furthermore, validating and comparing effects of the self-evasive action model in the simulation of the evacuation process is performed and finally, reproduce the CG movie of the evacuation process for giving better public understanding.

6.2 Average walking velocity for Malaysian Citizen

Currently, Malaysia is deficient in bank data of pedestrians walking velocity. This circumstance is quite detrimental since data of walking velocity is very beneficial for design of many infrastructures, health and safety purposes. With regards to the said circumstance, the author had carried out on-site video-based observational study on free walking of pedestrian in order to determine the average walking velocity. Besides, the pedestrian behavior of Malaysian citizen is also obtained.

From the analysis, the determination of average walking velocity with samples of 1092 pedestrians was attained successfully. The determination of average walking velocity was made based on different age of groups (5-9, 10-39 and 40-69 year-old) and gender (male and female). The obtained average walking velocities were then used in the simulation of evacuation process.

6.3 Effectiveness and efficiency of the evacuation process

Overall, there were four hypothetical scenarios of tsunami evacuation process had been conducted at two different beaches areas namely, the Miami Beach, Penang Island and the Teluk Batik Beach, Perak in Malaysia. The simulations were performed by employing two types of simulators which are CBS-DE (without self-evasive action model) and CBS-DE with self-evasive action model.

For the tsunami evacuation process at the Miami Beach, the simulation was performed by using CBS-DE without self-evasive action model. At the beginning, the disadvantages area for smooth evacuation was firstly revealed and later the alternative evacuation process for improvements was investigated. The effects of the alternative evacuation process had been shown quantitatively.

In the second case study, the evacuation process against tsunami disaster at the Teluk Batik beach was investigated by using the CBS-DE without and with self-evasive action models. The significant effect of the introduction of the self-evasive action model had been found in the simulation results.

From the simulations conducted at two different beach areas, the completion time of evacuation for different scenarios were compared. In conjunction with that, an effective and efficient evacuation process was investigated.

6.4 Validation and comparison of self-evasive effect

The effects of the introduction of the self-evasive action model were validated through; (1) comparison with the observation; and (2) investigation of the simulation results regarding the position distribution of the people.

In the first validation study, the validity of the self-evasive had been shown by comparing three different results, namely the model-1 (CBS-DE), the model-2 (CBS-DE with self-evasive action model) and the observation scene. From the simulated results the congested situation was occurred in the model-1. Meanwhile, in the model-2, the alignment of pedestrian, which were similar to the observation scene, was found. From the validation, introduction of the self-evasive action model is effective to simulate the pedestrian behavior.

In the second validation study, two types of test areas were referred: the one is the area showing the contraflow, the other is the area showing the unidirectional flow. The purpose of this validation was to show the effects of the introduction of the self-evasive action model in the contraflow and the unidirectional flow. From the findings of the test area for the contraflow by the model-2, the people tend to follow the front people rather than make their own path to evacuate. This action influences the formation of alignment in the contraflow condition. And this also contributes to form the smooth contraflow during bidirectional crowd flow. Unlike in the model-1, the significant congestion with crowd cannot be found. On the other hand, in the test area for the unidirectional flow, the movement of simulated people by the model-2 is more scattered than that by the model-1. The movement of simulated people by the model-1 appears to be organized in forming a line. In the evacuation process, it is hard to consider the evacuation behavior in line. From this point of view, the scattered evacuation behavior by the model-2 might be natural.

6.5 The CG movie of evacuation process

The CG movie of evacuation process is one of the crucial parts in this research. From the simulation results, the positions of each person were tracked with detail information. Through the detail information obtained, creating a realistic virtual space by CG movie is possible and the visualization of the evacuation process would be a useful for giving the information to the public in understandable manner.

6.6 Future plan

The author would like to propose some research plan in the near future. All of the current simulations shown in this doctor thesis are performed by using the Crowd Behavior Simulator for Disaster Evacuation (CBS-DE), in which individual person is modeled without considering group behavior. However, in the actual evacuation process, crowd behavior would be formed by assembled small group unit such as family or couple friend. For that reason, modeling of group behavior is crucial to be developed.

In addition, tsunami disaster can range up to the scale of a coastal town. Therefore, the implementation of massive evacuation simulation under the order of several kilometers in length scale and several hundred-thousand of persons should be investigated by utilizing GPU computing with consideration of computer efficiency.

And finally, it is better to perform a simulation by also considering the effect of inundation scenario of tsunami simultaneously with the evacuation process simulation so that it is more realistic in simulating a critical state of evacuation.